THE DEVELOPMENT AND USE OF HYDROLOGICAL/ WATER QUALITY MODELS FOR THE MANAGEMENT OF CONTAMINATED WATER RELEASES INTO THE MAGELA CREEK, NORTHERN TERRITORY.

by

Richard John Goldberg, B.Sc. (Technology),
Dip. Ed.

A dissertation submitted in partial fulfilment of the requirements for the degree of Master of Environmental Studies in the Australian National University.

December 1978.

DECLARATION

Except where otherwise indicated, this dissertation is my own work.

R. Goldberg

R.J. GOLDBERG

December 1978.

ACKNOWLEDGEMENTS

This project has been carried out at the Centre for Resource and Environmental Studies, A.N.U., while the author was supported by a Commonwealth Post-Graduate Course Award.

The author is grateful to R. Ash of the Department of Transport and Works, Northern Territory, for the provision of hydrological data on the Magela Creek and to D.I. Smith, Prof. P. Young and P. Whitehead, for their advice and interest.

ABSTRACT

The proposed development of certain uranium mines in the Northern Territory will involve the discharge of contaminated water into the Magela Creek. This report discusses the role of computer-based hydrological/water quality models in the management of these releases. The aim of any such management program would be to minimise any associated adverse environmental impacts. Various modelling approaches are reviewed and some preliminary modelling studies are undertaken.

The paper describes a streamflow model which is based on a simple ordinary differential equation model. for flow routing in the mainstream and is augmented by a stochastic time-series model to account for rainfall-runoff processes. An ordinary differential equation model for longitudial dispersion, based on simple mass balance principles, is examined as a basis for a water quality model, and the model results are compared with data derived from a dye tracing experiment in the upper reaches of the Magela Creek. The results of these preliminary studies indicate that the modelling approaches examined are worthy of further development to test their suitability as a basis for a water release management strategy.

CONTENTS

PAGE

LIST OF FIGURES

LIST OF PLATES

CHAPTER 1

INTRODUCTION

1.1 PREAMBLE

The proposals for the development of the uranium ore deposits in the Alligator Rivers Region of the Northern Territory (see figure 1) have involved substantial public debate and have aroused considerable opposition. Opponents of the proposals have argued that the environmental risks are of such a nature and magnitude that Ausralia should not export or mine uranium at all. These risks and and dangers range from possible adverse impacts on Aboriginal society and radiation hazards to wider and more indirect issues such as increased risks of nuclear war and problems concerning the disposal of radio-active wastes.

This project is, however, only concerned with examining one aspect of the total environmental impact of the proposed development, namely, the potential water pollution problem associated with the mining and milling of the uranium ore. More specifically, the aim is to examine the role of hydrological/water quality models in the overall management and control of any contaminated water releases to the Magela Creek.

1.2 OBJECTIVES OF THE PROJECT

The objectives of the project are:-

(a) to briefly assess the need for modelling of the Magela drainage system.

(b) to review the various modelling approaches which are detailed in the hydrological literature.

(c) to undertake some preliminary hydrological modelling using streamflow and rainfall data from the Magela Creek catchment.

(d) to assess the suitability of the dynamic hydrological models used by the Applied Systems Analysis Group at CRES for application to the Magela Creek System.

(e) to undertake some preliminary water quality modelling using the results obtained during a dye tracing study carried out in the Magela Creek during March, 1978.

(f) to recommend, on the basis of these preliminary studies, the data which would be useful to any further modelling development and the type of field surveys which would most effecively contribute to the limited data currently available.

1.3 THE MAGELA CREEK SYSTEM

Specific aspects of the Alligator Rivers Region have been described in detail in a number of publications. (e.g. C.S.I.R.O., 1969, 1976; Conway *et al*, 1974; Ranger Inquiry, 1977; Christian and Aldrick, 1977). The uniqueness of the area results from a combination of features which include; the wide range of biological habitats and their richness in species; the association in close proximity in parts of the Region of plateau, lowlands, flood plains and rivers; the fact that aboriginal people in the Region continue to have strong traditional links with the land; the presence of important archeological sites and examples of aboriginal art, and the high conservation value of the Region. (Ranger Inquiry, 1977, p.21).

The Magela Creek and its catchment are comparable to the other streams and catchments in the Region. (See figure 2). Two distinct seasons occur in the area; an almost rainless dry season from May to September and a wet season from November to March. The rainfall regime of the area has three major characteristics; it is highly seasonal, high reliable (on both an annual and monthly basis) and in average terms does not appear to vary greatly in seasonality or amount from place to place (McAlpine, 1976, p. 39). Five categories of rain producing systems have been distinguished for this area (Southern, 1966). They are:-

i) Equatorial or monsoonal troughs usually producing widespread cloud and rain - late December to April.

ii) Tropical cyclones producing very heavy rain but usually in restricted areas only - late November to May.

iii) Regional convection resulting in widespread precipitation - late September to early January.

iv) Local convection resulting in local showers or thunderstorms - September to May.

v) Easterly disturbances which prolong the wet season in some years in East Arnhem Land - April to June.

Annual rainfall averages over 1500 mm in the vicinity of Darwin and decreases by approximately 390 mm for each 65-80 kilometres in the south-east direction

(Department of Northern Territory, 1973, p. 1). Annual evaporation exceeds rainfall and is approximately 2200 mm with a monthly maximum of 260 mm in October and a minimum of 100 mm in February (McAlpine, 1976, p.42).

In an average year, wet season flow in the Magela Creek occurs from about mid December to the end of June, and total flow past Jabiru is about 250 million cubic metres but may range from 3 times this volume to less than a quarter (Ranger Inquiry, 1977, p.59). Except in upstream sections fed by springs or seepage, flow stops during the dry season, leaving chains of isolated billabongs and swamps.

Upstream of Mudginberri billabong, the creek comprises stream lines which are reasonably well-defined but are shallow and extensively braided. It is in this section that the proposed water releases from the Ranger site will be made. Results of a dye tracing experiment (see Chapter 3) indicate that, despite the braided stream lines there appears to be effective mixing provided by the uneven bottom and heavy tree growth even under relatively low flow conditions. This is a desirable characteristic from the point of view of any contaminated water releases and is evident from Plates 1 and 2 which also show the heavy tree growth typical of the river section in the vicinity of the proposed release points.

The section of river between Mudginberri billabong and Jabiluka billabong comprises a series of stream channels, waterholes and flood plains. Examples of these billabongs may be seen in Plate 3 which also shows the flood plains and part of the escarpment in the distant background. Waste water releases from the Jabiluka operation are proposed for a site just upstream of Jabiluka billabong (Plate 4). Although water velocities in this section are much lower than further upstream, Pancontinental claim that turbulence conditions will result in effective dispersion for the flow rates at which releases are planned. (Pancontinental, 1978, p. 44).

Downstream of Jabiluka billabong, the Magela flood plain (Plate 5) covering approximately 160 square kilometres merges with the riverinal plain of the East Alligator River.

Detailed Magela Creek data relating to water quality, critical habitats, the fate of dissolved trace elements, the pollutant tolerance levels of organisms and various radiological aspects such as exposure routes and biological concentration factors, are of obvious importance in the determination of water quality standards and contaminated water release procedures for the proposed uranium mines. Some information on these aspects has already been published (e.g. Davy, 1973; Davy and Conway 1974; Giles, 1974) and was summarised and commented on by the Fox Commission (Ranger Inquiry, 1977).

The river water is generally very soft and slightly acidic with low levels of heavy metals and suspended solids. The extent of water quality deterioration during the dry season varies from year to year and in different parts of the Magela system, but the general trends are increases in water temperature,

<u>PLATE 1</u>

Typical Magela Ck. Section near Injection Point. (Shows passage of dye pulse during tracing experiment).

North

PLATE 2 Typical Magela Ck. Section near Gauging Station G.S.821009 (from 600 metres) (Shows passage of dye pulse during tracing experiment)

PLATE 3 Island Billabong (looking North)

PLATE 4 Jabiluka Billabong and Adjacent Flood Plain concentration of dissolved substances, acidity, turbidity and anaerobic conditions. These various changes interact in a complex way in influencing the chemical form of toxic contaminants such as heavy metals and the consequent effects of these changes on the biota are poorly understood. Davy and Conway (1974, p.29) conclude that the 'non-radioactive heavy metals are the most restrictive waste constituant for the formulation of discharge authorisations'.

PLATE 5 Jabiluka Billabong and Adjacent Flood Plain (Looking North)

1.4 CONTAMINATED WATER RELEASES

Apart from certain major social impacts associated with the proposed uranium mining (e.g. impact on aboriginal society), the possibility that contaminated water from the mine sites could cause environmental damage downstream is one of primary concern.

The Review Report of the Alligator Rivers Study concluded that the limited amount of information on the responses of some biological species to possible wastes from mining development indicate a 'need for restraints on significant additions of heavy metals or radioactive materials to certain drainage systems, if adverse effects on the environment, man and other biota are to be avoided'. (Christian and Aldrick, 1977, p.153).

In the case of the mining operations at Jabiru and Jabiluka, contamination of the waters of the Magela Creek will occur from both controlled and uncontrolled releases of water. (Ranger Uranium Mines Pty. Ltd., 1974; Pancontinental Mining Ltd., 1977).

Although it is proposed that liquids used in the milling operation will be re-cycled and that none are to be released to the environment, some seepage together with contaminated runoff from the mine and mill areas will initially be contained in a retention system. The major pathways by which contaminated water would enter the Magela Creek are shown in Figure 3 for the case of Ranger.

Although a 'no release' situation would be the ideal, in the case of Ranger, the evidence before the Fox Commission suggested 'that releases might have to be made at times, even if all feasible alternatives were implemented'

(Ranger Inquiry, 1977, p.112). Controlled releases of contaminated water from Ranger would be made directly to both Magela Creek and its tributary, Coonjimba Creek; and in the case of Pancontinental, releases would be made to Magela Creek after dilution in a dilution pond.

The Commission recommended that the water management system be established initially such that no intentional releases to the environment would be required, and that this system be maintained until it is shown that releases of contaminated water would have to be made. (Ranger Inquiry, 1977, p.327). If, however, releases are found to be necessary, the strategy suggested by the Commission is designed to maximise the possibility that contaminants will be flushed out of the Magela Creek system and that contaminants, while still in the system, will be of sufficiently low concentration that adverse environmental effects are avoided.

It should be noted that the details of the water release schemes, as originally described in the Environmental Impact Statements of both Ranger and Pancontinental, and in the Second Report of the Fox Inquiry, may well be modified further to comply with water quality standards and codes of practice which have yet to be specified.

CHAPTER 2

THE NEED FOR MODELLING OF THE MAGELA SYSTEM

Both Ranger and Pancontinental used computer models for calculating a water and contaminants balance on their mine sites and for estimating quantities of runoff and seepage. These models were based on rainfall, evaporation, runoff and infiltration data obtained from the mine sites, together with data from Oenpelli and Darwin meteorological statistics and from C.S.I.R.O. records. Data from laboratory and field heap leaching tests were also used as inputs to these models.

Computer simulations were used in assessing other aspects of the water management programs, such as the dilution and dispersion characteristics of the Magela Creek in the vicinity of the proposed Ranger discharge structure.

The Commission, however, was reserved in its acceptance of the results of the Ranger modelling studies, as the models were largely untested (Ranger Inquiry, 1977, p. 93, 107). A major problem in the development of these models was the poor quality data on which they were based. In fact, 'the Commission encountered a general problem of inaccuracies and inconsistencies in the data which were presented, and lack of data on some important questions' (Ranger Inquiry, 1977, p.89.)

These uncertainties related to off-site* information on the Magela system itself as well as to the calculations made about on-site* water volumes and contaminant loads.

Despite the field work in the years since the ore bodies were located, many aspects of the Magela system are characterised by lack of information. Deficiences include hydrological and water quality data as well as information on biological uptake and toxicities of heavy metals. The Commission accepted that 'existing information is not sufficient to enable the ecological effects of mining, especially long term effects on aquatic ecosystems, to be predicted' (Ranger Inquiry, 1977, p.69).

However, low quality of experimental data combined with uncertainties as to the system behaviour are typical characteristics of large complex, natural systems (Young, 1978; Vansteenkiste, 1976). The development of a mathematical model of a system can assist in determining important mechanisms and control variables, and in establishing data collection and analysis procedures (Whitehead, 1977). In addition to a model's ultimate role as a tool for management and control, the modelling process itself is useful in guiding physical experimentation and establishing the type and frequency of field observations needed (Biswas, 1975; Andrews, 1974) and is therefore important in helping to make best use of

* 'On-site' refers to the area within the mining lease on which mining and milling operations will take place.

'Off-site' refers to the entire Magela Creek system outside the boundary of the mining and milling operations.

scarce and costly research resources.

The need for a comprehensive meteorological-hydrological - water quality model of the Magela system was recognised by the Fox Commission who stated that

> 'Such a model will be essential for interpreting monitoring data and predicting effects. It will be equally essential for planning any waste water releases... The model will be a product of, and a vital component in, the integrated research and monitoring program'. (Ranger Inquiry, 1977, p.296-7).

In accordance with these suggestions, and in addition to the primarily on-site models referred to earlier, the mining companies are currently engaged in developing models of the Magela Creek system itself, to be used in conjunction with on-site models for release planning and control purposes. Pancontinental, for example, report that

> 'The final scheme to be developed.... is anticipated to be a computer based hydrological model, fed directly with telemetered information from rainfall and flow gauging stations, and with analytical results from the companies' monitoring programme. The model will be capable of testing release options for both the Ranger and Jabiluka Projects and allowing the companies to decide optimum release strategies.' (Pancontinental Mining Ltd., 1977, p.118).

The Fox Commission specified that the hydrological-meteorological-water quality model should have certain capabilities in relation to the establishment of release conditions for contaminated water. The model should be able to indicate the probability that continuous flow between Jabiru and gauging station G.S.821019 will persist long enough at the end of the wet season for discharges from Jabiru to reach the East Alligator River. It is implied that this release condition should be stated in terms of flow past Jabiru (Ranger Inquiry, 1977, p.114).

> 'Operations during the wet season would need to balance the conflicting requirements to release sufficient water from retention ponds No. 1 and No. 2 so that these ponds could contain heavy runoff which might occur in the late stages of the wet season, and at the same time to retain enough water at the end of the wet season to supply the mill circuit during the subsequent dry season. Releases would not be made at the end of the wet season, because of the greater risk then that contaminants would be retained in the Magela system through the following dry season.' (Ranger Inquiry, 1977, p.91).

Apart from the use of a model for determining the most suitable timing for releases, there are other aspects of the water management program for which a model may be useful. There is, for example, a great deal of uncertainty associated with the flow conditions required in Magela Creek relative to Coonjimba Creek to ensure that releases to the latter from retention pond No. 1, will not be trapped, due to 'backflow'. A suitably designed model could possibly assist in defining the flow conditions required to ensure flushing of contaminants from Coonjimba Creek to Magela Creek.

CHAPTER 3

DYE TRACING EXPERIMENT

To provide further information on the hydrology of the Magela Creek system, the Office of the Supervising Scientist commissioned the Applied Systems Group of the Centre for Resource and Environmental Studies to undertake a fluorometric dye tracing experiment in March, 1978 (Smith *et al*, 1978a, 1978b).

Among the many aims of this experiment, two were of relevance to this project, namely:-

(a) to gain information on the dispersion characteristics of the river system,

and

(b) to provide data for hydrological and water quality modelling studies of the Magela Creek system.

Tracers of various kinds have been used for a number of years in hydrological studies such as streamflow measurement (e.g. Dincer, 1967), groundwater tracing (Smart and Smith, 1976), transverse mixing (Yotsukura *et al*, 1970), longitudinal dispersion (Whitehead *et al*, 1978b), time of travel measurement (Pilgrim, 1977, 1976) and dispersion in a tidal embayment (Fischer, 1972). On this occasion, Rhodamine WT dye was selected as the tracer as it had been developed specifically for hydrological applications and has low toxicity and good resistance to absorption and photochemical decay (Smart and Laidlaw, 1977).

The method used was to inject 90 litres of dye (16 kg dry weight) into the river at the proposed discharge site for the Ranger operation. Samples were collected from a series of sites downstream (See Figure 4) and analysed for dye concentration with two Turner fluorometers using techniques described by Wilson (1968).

The data resulting from the dye tracing experiments are useful to the hydrological and water quality modelling studies in a number of ways.

(a) The average streamflow velocity between the injection site and various sampling stations downstream can be determined from the travel time of the dye mass. These velocity results, together with the corresponding discharge measurement, enable identification of the a and b parameters in the relationship, $v = a.Q^b$ between velocity v and flow Q, which is used in both the streamflow and water quality models described in later chapters. Ideally, a number of similar dye tracing studies under differing discharge conditions, are needed to accurately define the a and b parameter values at each of the various sections of the Magela system. This is discussed further in Section 4.1.2.

(b) The graphs of dye concentration versus time at various downstream locations can be used to assist in selecting the most appropriate model structure for the water quality model and in defining certain of the parameter values required (e.g. number of reaches needed for each modelled river segment).

(c) The water quality model developed in this study only accounts for longitudinal dispersion and is based on the assumption that any soluble contaminant will be homogeneously distributed over the cross-section of the river. Data from the dye tracing experiment indicate how closely this assumption is realised in practise and define those parts of the Magela system where some care would be needed in interpreting any model output. For example, the experimental results showed that in Mudginberri billabong (site 3, Figure 4), there was considerable stratification with depth, and the peak dye concentration and time of arrival varied over the cross-section. Similar heterogeneity was observed at other downstream cross-sections especially on the flood plain.

(d) The data from further tracing experiments conducted under different flow conditions would be useful for validating any water quality model.

Some results from the tracing experiment are included in this project (Section 5.3), but only as a means of comparing the output of the water quality (longitudinal dispersion) model with observed field data.

CHAPTER 4

STREAM FLOW MODELLING

The approach taken in this project in modelling the Magela Creek streamflow is similar to that which was succesfully utilised for the Bedford -Ouse Water Quality Study in England (Whitehead and Young, 1975) and the Lower Murrumbidgee Study (Whitehead *et al*, 1978b; Watercres, 1978). The river system is broken down into a number of sequential reaches and each reach is modelled to account for both dynamic and stochastic behaviour.

A simple deterministic hydrologic storage method of flow routing is used to estimate the flood hydrograph at downstream points based on a known hydrograph at an upstream location. Rainfall/runoff effects between the upstream and downstream points are modelled by a stochastic time series technique and combined with the output of the simple routing model to produce a final outflow hydrograph. This total streamflow model (see figure 5) may be used as a means of forecasting flow and also as a source of hydrological data for a water quality model. It should be mentioned here that other approaches to streamflow modelling are common. In these, there is no decomposition of the streamflow model into mainstream flow routing and rainfall runoff components.

The flow routing component of the total streamflow model was developed for use on the CRES Tektronix 4051 mini-computer and the rainfall-runoff component was modelled on the Univac 1100/42 computer.

Having identified an appropriate model structure and estimated the model parameters for the rainfall-runoff component, this model was incorporated with the flow routing model on the Tektronix 4051 mini-computer to produce the total streamflow model.

It should be emphasised that the modelling studies described in this project represent only the initial steps in a complete study. The intention is not to produce models which are developed sufficiently for actual application in a water management program, but rather to test the suitability of the models for use on the Magela system and to define areas in which further development work is required.

4.1 FLOW ROUTING MODEL

It has been found in practice that simple routing methods have much to recommend them and are adequate for most purposes (Price, 1975; Weinmann and Laurenson, 1977). In this project, the flow routing equation is derived by analogy with the 'lumped parameter' or ordinary differential equation model for the variations in the concentration of a conservative pollutant. Details of this derivation may be found in Whitehead *et al* (1978c).

Briefly, however, by using a probabilistic argument, an analogy is drawn between the variations or 'perturbations' in flow δQ about some mean or reference level and the changes in concentration of the conservative pollutant (Himmelblau and Yates, 1968).

The resulting equation takes the form:-

$$K \frac{d\delta Q}{dt} = \delta I - \delta Q \qquad (1)$$

K = 'time of travel' parameter (or storage coefficient)

Q = output flow

I = input flow

Equation 1 represents the flow processes in a single reach and has some similarities with the well known Muskingham method (Chow, 1964; Laurenson 1978). This latter method is based on the following equations:-

$$\frac{dS}{dt} = I - Q \qquad (2)$$

$$S = K\left[xI + (1-x)Q\right] \qquad (3)$$

where S = reach storage

x = a dimensionless dispersion parameter.

Whitehead *et al*,(1978a, p.19) have shown that 'in control and systems terms, the general Muskingham method is over-parameterised since it has two parameters where only one is necessary to obtain the described behaviour'.

As shown by Laurenson (1962), the value of N (the number or reaches) cannot be chosen independantly of x and larger values of N require smaller values of x.

A value of $X = 0.5$ results in pure *translation* of the flood wave and values of $X < 0.5$ introduce numerical distortion, similar to a diffusive term, thus leading to an *attenuation* of the wave (Weinmann and Laurenson, 1977). A value of $X = 0$ corresponds to a fully *concentrated* or reservoir type action where inflow causes an instantaneous response, the principal effect being attenuation of the inflow peak (Weinmann and Laurenson, 1977, p.139). With $X = 0$, the translation effects can be simulated by using an appropriate number of concentrated storages in series. This approach has been used successfully in other studies (e.g. Whitehead *et al*, 1978b; Whitehead and Young, 1975) and achieves a similar effect to the lag and route models, where the inflow is first translated and then routed through a reservoir (Weinmann and Laurenson, 1977). This technique is adopted here, and with $X = 0$, equations 2 and 3 reduce to:-

$$\frac{dQ}{dt} = \frac{1}{K}(I - Q) \tag{4}$$

where K, the travel time is represented as a function of discharge. The similarities between equations 1 and 4 will now be obvious.

The non-linear relationship between travel time and discharge may be determined in a number of ways. In the Bedford-Ouse Study (Whitehead and Young, 1975,) for example, a simple volume-flow relationship based on reach characteristics was adopted, whereas the Murrumbidgee Study (Whitehead *et al*, 1978b) used a storage coefficient determined from the relationships:

$$K = \frac{l}{v} \tag{5}$$

and $$v = a.Q^{b} \tag{6}$$

where l = reach length (m)

v = mean flow velocity (m/s)

and a and b are constants.

This method of introducing a time varying storage coefficient provides a convenient and simple method of flow routing and avoids the negative flows which are sometimes associated with the Muskingham method when values $x \neq 0$ are used (Nash, 1959).

Equation 6 derives from the work of Leopold and Maddock (1953) in which they observed that, in a natural stream, the width, depth of channel and the velocity are related to discharge in the form of simple power functions. In the present project, the values of parameters a and b were estimated on the basis of data obtained from the tracer experiment conducted in the Magela Creek (Smith *et al*, 1978a, 1978b) together with data made available by the Water and Sewerage Division of the Northern Territory Department of Transport and Works.

The simple reach model of equation 4 can be represented approximately in Laplace Transform terms by taking the 'slowly varying' storage coefficient outside the differential operator:

$$A = \frac{1}{(1+Ks)}. \ I \tag{7}$$

where s is the Laplace operator

and $\frac{1}{1+Ks}$ is the transfer function between I and Q.

For N reaches in series, the overall transfer function F(s) becomes:-

$$F(s) = \frac{1}{(1 + Ks)^N} \tag{8}$$

With this model structure, there are three parameters to be specified in order to apply the routing procedure: a, b and n.

<u>4.1.1 Estimation of Model Order</u>

The model order N (number or reaches) can be calculated from certain hydraulic characteristics of the river system or it can be derived by fitting computed to observed hydrographs.

The former approach was used by Whitehead *et al*, (1978, p5) who showed that 'N must equal half of the Peclet number if the non-linear storage method is to reproduce the convective-dispersive nature of the flood wave propagation phenomenon', where the Peclet number can be determined from channel characteristics such as width, slope and depth. Their experience has shown that parameters selected for relatively high flow conditions produce reliable predictions for a wide range of flows, and that, in any case, the routing method is quite insensitive to the value of N (Whitehead *et al*, 1978a, p.17).

However, cross-sectional area, hydraulic radius and slope often vary markedly within reaches of natural streams (Pilgrim, 1977) and in the case of the Magela Creek, even in the upper reaches, the water level of the main channels frequently exceeds bankfull and it is extremely difficult to arrive at parameter estimates of depth or width. For this reason, selection of the number of reaches for flow routing was made by the trial and error fitting approach referred to earlier.

The effect of changing N can be seen in figures 6a, 6b and 6c, in which N takes values of one, two and three respectively, and in which flow at G.S. 821009 is modelled using upstream flow at G.S.821008 as the input. Although the model output shown is not complete, due to the absence of the rainfall/runoff component between the two sites, the figures show the translation or delaying effect of an increasing number of reaches. It is not possible to determine the most appropriate number of reaches for this section of river from these figures due to the lack of the rainfall/ runoff component. However, as we shall see, further modelling, using more complete data indicated that 1 reach was suitable.

4.1.2 Estimation Of a And b Parameters

The empirical relation between average velocity and discharge at-a-station (equation 6) was originally developed by Leopold and Maddock (1953) who, in studies of 20 river cross-sections, representing a large variety of rivers in the Great Plains and the Southwest of the U.S., found an average value of 0.34 for the b parameter. Further empirical evidence, listed in Table 4.1., suggests that the value of b usually ranges from about 0.3 up to 0.6.

TABLE 4.1

VALUES OF b PARAMETERS IN THE AT-A-STATION RELATION

$$V = a.Q^b$$

DATA SOURCE	SITE	VALUE OF EXPONENT b
Wolman (1955)	Brandywine Ck., Pennsylvannia	0.55
Leopold *et al*, (1964)	Average for 158 U.S. Gauging stations	0.43
	Average for 10 Gauging stations on Rhine River	0.43
Leopold and Miller (1956)	Average for ephemeral streams in semiarid U.S.	0.32
Calkins and Dunne (1970)	Small mountain stream, Northeast Vermont	0.41 -0.49
Pilgrim, (1976)	Average for small watershed near Sydney N.S.W.	0.47
Whitehead *et al*, (1978b)	Lower Murrumbidgee N.S.W.	0.57

The exponent values in the last three examples of table 4.1 were all derived from tracer studies in which the average velocity, over a reach of stream, was calculated from time of travel of the centroid of the tracer pulse. It is of interest that these b parameter values are of the same order of magnitude as the at-a station * values previously reported where conditions were not necessarily representative of the entire stream segment.

Although the values of the a and b parameters can be derived using the hydraulic characteristics of the channel, such values, derived from theoretical considerations only provide crude approximations and, in general, cannot be used to generate reliable flow forecasts. (Whitehead *et al*, 1978a, p.20).

A more satisfactory approach used in hydrological modelling studies of the Murrumbidgee River (Watercres, 1978) is to evaluate these parameters from experimental data gathered from the river segment for which the model is to be used. In these studies, several dye tracer releases were made under different discharge conditions. This enabled calculation of both the average velocity over a stream segment and the discharge. A logarithmic plot of velocity versus discharge gives a straight line from which the a parameter is determined as the intercept and the b parameter as the slope.

The variability of stream widths and bed roughness makes it impractical to measure the velocity at a particular cross-section and use it as the average velocity through the segment (Calkins and Dunne, 1970).

* 'At-a-station' values for a and b apply to a relationship between velocity and discharge *at a particular cross-section*, where each discharge on these at-a-station curves represents an occurrence of different frequency. This is to distinguish from a and b values which apply when several cross-sections along the length of a stream are compared only for some constant frequency of discharge.

For example, average velocity (v) and flow (Q) data supplied by the Northern Territory Department of Transport and Works, for specific gauging stations on the Magela Creek are plotted in figures 7 and 8. Figure 7 gives the relationship between v and Q for 3 sites all within 250 m of the gauging station G.S.821008, and shows the variability which can occur even with locations in close proximity. Figure 8 shows the relationship at gauging stations G.S.821009 and G.S. 821019 which have quite different a and b values to those at G.S.821008.

The advantage of the tracing technique is that it overcomes the errors involved in selecting a 'representative cross-section'. In the Magela Creek study (Smith *et al*, 1978b) only one dye release was made, and so a and b values representative of a whole river reach could not be precisely defined. However, a range of possible combinations of a and b parameter values has been determined. These are shown in figure 9 and are based on the dye dispersion data for the river segment between the injection point and site 2. (see figure 4).

Despite the lack of experimentally determined a and b values for whole river segments of the Magela Creek, some choice of values was required in order to undertake both the streamflow and water quality modelling studies of this project. In the case of the longitudinal dispersion model (see Section 5), for example, a value of b of 0.4 was selected for the river segment from the injection point to site 2 having regard to the at-a-station values determined at G.S.821008 and G.S.821009 (figures 7 and 9), the typical values listed in table 4.1, and the theoretically determined value based on the Manning's equation and the Kleitz-Seddon principle (Whitehead *et al,* 1978a, p.25-26).

For b = 0.4, the associated a parameter value of 0.117 was taken from the graph of a versus b in figure 9. Despite the inaccuracies inherent in the use of hydraulic characteristics in determining values of a and b due to the simplifying assumptions involved, application of these methods confirms that this value of a is a reasonable first estimate (See Appendix 1). Clearly, however, further work will be required as more data becomes available to further refine the estimates.

4.1.3 Modelling Of The Bank Storage Effect

When the first flows occur at the start of the wet season, a certain fraction of the water comprising the flow at an upstream location, e.g. gauging station G.S.821008, does not subsequently appear as part of the flow at downstream locations such as G.S.821009. This is due to infiltration into the bed and banks of the river. Although less apparant, this same process would occur later in the wet season if heavy flows follow a relatively dry period.

To account for this effect, two different approaches were tried. In the first, the upstream input flow to the model is modified by a 'low-pass' or lag filter (similar in form to that used in the rainfall-runoff model described later in Section 4.3.2.2) to produce an effective input flow. In the second, the upstream input flow was modified by a 'short-term' filter which rises exponentially from zero to 1.0.

Data from the 1977/78 wet season was used for these initial modelling runs. However, the entire wet season flow record was not used as complete rainfall records were not available beyond 1.3.1978. Consequently all modelling using 1977/78 data for the river section from G.S.821008 to G.S.821009 was only for the period 1.11.77 to 1.3.78, and did not include the latter part of the wet season.

4.1.3.1. Low Pass Filter Technique

The upstream input flow is modified as follows:-

$$Q'_k = Q_k . Bn_k \tag{9}$$

where Q'_k = effective input flow at time k

Q_k = actual input flow at time k

Bn_k = normalised bank storage factor at time k

The bank storage factor series, Bn_k, is obtained from the discrete first order filter:

$$B_{k+1} = B_k + \frac{1}{Tc} (Q_{k+1} - B_k) \tag{10}$$

and the series B_k is normalised to give Bn_k as follows:-

$$Bn_k = \frac{B_k}{B_{max}} \tag{11}$$

where B_k = bank storage factor at time k

$$\left. \begin{array}{l} B_{max} = \max B_i \\ \qquad i = 1, \ldots\ldots x \end{array} \right\} \; x = \text{total number of data points}$$

Tc = bank storage time constant

Bn_k takes values between 0 and 1 and has the effect of reducing the actual upstream input flow by an amount dependent on the weighted average of previous flows. The low pass filter is simulating the 'lag effects' associated with the influent seepage through the banks and bed of the river and the value of Tc is indicative of the dynamics of these processes.

The effect of this bank storage factor can be seen in figure 10, which shows the outputs of the flow routing model for flow during the 1977/78 wet season at gauging station G.S.821009, with and without the use of the bank storage factor. It can be seen that the inclusion of this factor to modify the input flow at G.S.821008 leads to a reduced model output at the start of the wet season when the bank storage effect is large. As the wet season progresses, this effect is reduced, although after a long period of relatively low flow, such as from day 70 onwards, the bank storage effect again exerts considerable influence on the level of output flow.

<u>4.1.3.2. Short Term Filter Technique</u>

The upstream input flow is modified as follows:-

$$Q'_k = Q_k . Bs_k \tag{12}$$

where Bs_k = short term bank storage factor at time k.

The series Bs_k is obtained from the following:-

$$Bs_{k+1} = Bs_k + \frac{1}{Tc}\left[1 - Bs_k\right] \tag{13}$$

For the flow routing model in which the time series data starts with the very first flows at the beginning of the wet season, the initial value of Bs_k is set at zero, (i.e., $Bs_0 = 0$) and thereafter it rises to approach asymptotically to one.

The effect of this bank storage factor can be seen in Figure 11 which shows the outputs of the flow routing model at G.S.821009 for the same 1977/78 input data used in figure 10. Unlike the low pass filter technique of figure 10, the influence of this short term filter in modifying the actual input flow is continuously diminished as the wet season progresses, irrespective of subsequent flow variations.

For a river cross section approximating a rectangular shape, this short term filter technique is probably more realistic than the low pass filter as the river bed is covered by water throughout the wet season and increased flows would not be expected to cover substantially larger areas of previously exposed surface. In these circumstances, such as would occur in headwater sections of the Magela Creek, bed infiltration losses due to flood flows late in the season would probably be minimal. Only in river sections where flood flows cover large areas of previously exposed surface, would the low pass filter technique possibly be more realistic.

Although the short term filter may be a reasonable technique to apply at the start of the wet season, it is quite obviously unsuitable for application at the end of the wet season as the value of the bank storage factor Bs_k remains at a value of unity. This precludes the effective input flow Q'_k from declining back to zero at the end of the wet season. The low pass filter described previously does not have this deficiency.

Further studies may reveal that neither the short term filter technique or the low pass filter are completely suitable in describing the bed infiltration phenomena and that both are only crude approximations to the complex infiltration processes actually occurring in the river bed. Despite these possible shortcomings, however, both these techniques were used in the streamflow modelling in keeping with the aim of developing very simple models. Of course, the simplicity of the model is not indicative of crudity in itself and it is quite possible that a simple model will perform as well as a more complex model. If the simple model consistently predicts successfully into the future, for example, then it can be considered adequate.

4.2 RAINFALL-RUNOFF MODELLING

4.2.1 Summary of Different Techniques

The rainfall-runoff process is a complex system of many phenomena which include 'interception by vegetative surfaces, infiltration into the soil surface, the dynamics of overland flow, storage in depressions, soil moisture re-distribution, aquifer flow, evapotranspiration in its several forms, and the dynamics of channel flow' (Porter and McMahon, 1971, p.298).

The hydrologic literature is replete with rainfall-runoff models which have been developed for the prediction of the response of a catchment to rainfall. These models range from the 'black-box' type (e.g. Whitehead and Young, 1975) which make no attempt to follow the physical movement of water through the catchment, to the 'process' model in which the attempt is made to simulate the separate and combined effects of each hydrologic component (e.g. Boughton, 1966; Porter and McMahon, 1971; Pattison and McMahon, 1973).

The 'process' or 'reductionist' models seem to have more appeal to hydrologists and many of them have become quite complex, with, for example, some seventeen parameters required to be fitted in the Stanford model (Crawford and Linsley, 1966).

Various hopes have been held and claims made for the use of process models in hydrology. The Australian Representative Basins Program (A.W.R.C., 1969) is, for example, developing a mathematical process model which, it is hoped, will prove suitable for use on ungauged catchments and for predicting the hydrologic effects of changes in land use on any catchment. It is sometimes claimed (e.g. Dunin, 1975) that process models increase the understanding of the hydrologic processes on a catchment. This would be achieved by examining the effects of each component on the outflow hydrograph and then investigating the degree of interaction between components (Mein, 1977). All of these claims and hopes are largely dependent on the modeller being able to associate the parameter values to measurable catchment characteristics.

Many practitioners are, however, sceptical about the possibility of these hopes for process models being realised. Mein and Brown (1976), for example, applied a modified Boughton model to the Thomson River and reported that even when the model performed well in predicting monthly streamflows, it would be difficult to show a statistically significant change in any single parameter due to some land use change. They found that seven of the ten parameters were quite insensitive to change and little confidence could be placed in the physical significance of their particular parameter values for that catchment.

A comparison of different modelling techniques was undertaken by the World Meteorological Organisation (W.M.O., 1975), who classified models as explicit moisture accounting (E.M.A.), implicit moisture accounting (I.M.A.) and systems approach. In this classification, the E.M.A. model is identical to the 'process' model and the models adopting the systems approach are identical to the 'black box' models referred to previously.

The 'black box' models vary slightly in their approach but they all account for the land-phase movement of water in a 'holistic' way rather than handling the component processes such as infiltration and evapotranspiration separately. The Constrained Linear System (C.L.S.) model, for example, uses as input a time series of precipitation data which is operated on by a series of kernel functions which transform the inputs into an outflow hydrograph (Todini and Wallis, 1974). Another approach, used in this project and described in more detail in Section 4.2.2, transforms the rainfall series into an 'effective' rainfall measure to account for factors such as soil moisture and evapotranspiration effects, and then uses techniques of time-series analysis to yield the runoff flow (Whitehead and Young, 1975).

The I.M.A. model, or serial storage type model (e.g. Sugawara *et al*, 1974) conceives of water being held in storage in a series of tanks representing the various storage zones in the soil mantle. The number of tanks and the size and positions of their outlets are defined by the model parameters.

Some conclusions emerging from the W.M.O. study have relevance to any modelling of the Magela Creek system. One such conclusion was that the accuracy of simulation among different types of models differs less in humid regions than in semi-arid regions but that in humid regions, during and immediately after a long, dry spell, the more complex E.M.A. models performed better than the simpler I.M.A. types (Sittner, 1976, p.208).

On the basis of these findings, it might therefore be argued that the E.M.A. model could be more appropriate for the modelling of the Magela Creek system which is subject to a long dry season each year. However, it was also noted, that when the models were applied to a catchment for which the data had rather large errors, the systems approach models performed better than the I.M.A. models which, in turn, performed better than the E.M.A. models.
'It was suggested that I.M.A. and systems models may be better able to filter out noise in the calibration data and more closely approximate the true parameter values' (Sittner, 1976, p.209). It was concluded that systems approach models may have a better capacity to cope with the deficiency of poor quality data and may therefore give

better forecasting results than E.M.A. models.

As discussed earlier (Chapter2), many aspects of the Magela Creek system are characterised by uncertainty and poor definition and so the systems approach may, therefore, be the most appropriate for hydrological/water quality modelling in this case, despite any possible disadvantages attached to the relatively poor performance of these model types in handling alternating dry and wet seasons.

If, as some authors claim, both 'process' and 'black box' models are generally equally effective in the simulation of streamflow (Weeks, 1977; Garrick *et al*, 1978), the choice of the most suitable model type for a particular application must be made by reference to the specific objectives of the study, the type and quantity of data which is available and the degree to which the operating mechanisms are understood.

4.2.2 Modelling Approach Of Present Project

The simple, deterministic flow routing model (described in Section 4.1) accounts for the major part of the outflow hydrograph, but does not account for the rainfall-runoff processes occuring along the river system downstream of the system boundary. This rainfall-runoff component of the streamflow output is incorporated by using a stochastic time series model, the details of which are described by Whitehead and Young (1975). This time-series representation is based on input-output analysis of the system in which runoff is inferred directly from the observed rainfall data after it has been transformed into an effective rainfall series.

The form of this model (see figure 12), is the discrete time-series or pulse (z) transform transfer function representation of a linear stochastic dynamic system and it is described in detail in Whitehead and Young (1975) and summarised in the remainder of this section. The runoff y_k results from the combined output of two models: One is a deterministic output x_k which is derived from the effective rainfall series u'_k and accounts for the major part of the runoff flow; the other is a stochastic output ξ_k which is derived from a white noise (i.e. serially uncorrelated) input series e_k . ξ_k explains that stochastic part of the runoff not accounted for by x_k and includes such factors as measurement noise and uncertainty on the system variables. The purely stochastic 'white noise' variable, e_k has zero mean and variance σ^2 and is uncorrelated both in time and with u'_k . The observed flow at time k, y_k, is given by the sum of deterministic but hypothetical 'noise free' component x_k and the stochastic component ξ_k. ξ_k is generated by an autoregressive moving average (A.R.M.A.) discrete-time model and x_k is generated by a transfer function model.

The form of this time-series model can be distinguished from other more conventional hydrological modelling techniques both by the use of a 'transfer function' representation and by the presence of the noise model. The incorporation of this stochastic influence is an admission that a purely deterministic model may not be completely adequate in an analysis which is based on field data about which there is an inevitable degree of uncertainty.

The model shown in figure 12 is characterised by the two 'transfer functions relating to x_k to u'_k and ξ_k to e_k. In the first case, the hypothetical noise-free runoff x_k is related to past values $x_{k-1},\dots x_{k-n}$ as well as to present and past values of the rainfall input u_k by the discrete time model:

$$x_k + a_1 x_{k-1} + \dots a_n x_{k-n} = b_0 u_k + \dots b_n u_{k-n} \tag{14}$$

Similarly the noise variable ξ_k is related to e_k by a discrete-time auto-regressive moving average(A.R.M.A.) model of the form:

$$\xi_k + c_1 \xi_{k-1} + \dots c_n \xi_{k-n} = e_k + d_1 e_{k-1} + \dots d_n e_{k-n} \tag{15}$$

In equations 14 and 15, $a_1 \dots a_n$, $b_0 \dots b_n$, $c_1 \dots c_n$ and $d_1 \dots d_n$ are parameters to be estimated.

The runoff output of this model, y_k is defined as the sum of x_k and ξ_k, i.e.,

$$y_k = x_k + \xi_k \tag{16}$$

Equations 14 and 15 can also be expressed in a convenient operational notation form by the introduction of the backward shift operator z^{-1}, where $z^{-1}x_k = x_{k-1}$

In this way, equation 14 can be reduced to

$$A\left[z^{-1}\right]x_k = B\left[z^{-1}\right]u_k \text{ or } x_k = \frac{B\left[z^{-1}\right]}{A\left[z^{-1}\right]}\cdot u_k \tag{17}$$

and equation 15 becomes

$$C\left[z^{-1}\right]\xi_k = D\left[z^{-1}\right]e_k \text{ or } \xi_k = \frac{D\left[z^{-1}\right]}{C\left[z^{-1}\right]}\cdot e_k \tag{18}$$

where
$$A\left[z^{-1}\right] = 1 + a_1 z^{-1} + \dots + a_n z^{-n}$$
$$B\left[z^{-1}\right] = b_o + b_1 z^{-1} + \dots + b_n z^{-n}$$
$$C\left[z^{-1}\right] = 1 + c_1 z^{-1} + \dots + c_n z^{-n}$$

$$D\left[z^{-1}\right] = 1 + d_1 z^{-1} + \ldots\ldots + d_n z^{-n}$$

Referring again to figure 12, it may now be seen that the transfer functions characterising the 'system model' and 'noise model' blocks are given by

$$\frac{B\left[z^{-1}\right]}{A\left[z^{-1}\right]} \quad \text{and} \quad \frac{D\left[z^{-1}\right]}{C\left[z^{-1}\right]}, \text{ respectively.}$$

This study utilised the *CAPTAIN* package of computer programs (*C*omputer *A*ided *P*rogram for *T*ime *S*eries *A*nalysis and the *I*dentification of *N*oisy *S*ystems) for the analysis of the rainfall-runoff data and the identification and estimation of the models shown in figure 12. The programs for this analysis utilise the instrumental variable approximate maximum liklihood (IVAML) method of time series analysis. A detailed description of the latest *CAPTAIN* package can be found in Venn and Day (1977). A description of the statistical techniques themselves is given in Young *et al*, (1971).

The estimation procedure is carried out by a recursive algorithm in which an estimate of the unknown parameter vector is updated recursively while working serially through the data. This recursive procedure allows for the possibility of parametric variation over the observation interval (Young, 1974). The approach is particularly useful where model parameters vary due to environmental factors which are not detailed in the model. As we shall see in Section 4.2.3, this technique can be used to track time varying parameters in a rainfall-runoff model and to relate these variations to evaporation and soil moisture changes (Whitehead and Young, 1975).

4.2.2.1 Transformation Of Actual Rainfall To Effective Rainfall.

Catchment yield can be considered as the residual remaining after subtracting initial loss and infiltration loss from storm rainfall. As already mentioned (Section 4.2.1), process models attempt to reproduce the behaviour of a catchment in physical terms by representing losses due to soil moisture storage, evapotranspiration loss, and depletion of soil moisture by drainage to groundwater etc.

Such a detailed approach was not found necessary on the Bedford-Ouse Study for which an effective rainfall series was derived from the observed rainfall data by using a low pass filter, equivalent in hydrological terms to an exponentially decaying antecedent precipitation index (Whitehead *et al*, 1978c, p24). This technique is adopted in the present project and is in keeping with the objective of ensuring that the model remains as simple as possible.

Soil moisture deficit effects are removed from the daily rainfall data by means of a discrete first order filter of the form:

$$S_k = S_{k-1} + \frac{1}{T}\left[u_k - S_{k-1}\right] \qquad (19)$$

where S_k = soil moisture index at time k

u_k = actual rainfall at time k

T = time constant associated with the hydrologic processes in the soil.

The soil moisture index series S_k is then normalised to give Sn_k, where

$$Sn_k = \frac{S_k}{S_{max}} \qquad (20)$$

$$\left.\begin{array}{l} \text{with } S_{max} = \max S_i \\ \qquad\qquad i = 1,\ldots.n \end{array}\right\} n = \text{total number of data points.}$$

The effective rainfall series is then obtained by modifying the actual rainfall series as follows:-

$$u'_k = Sn_k . u_k \qquad (21)$$

S_k is an exponentially weighted moving average of u_k and has the effect of reducing the actual rainfall series u_k after a period without rain. The time constant, T, is selected by a trial and error procedure in which the recursive estimation of the time-series model is repeated with different values of T until relatively time invariant recursive estimates of the parameters are obtained. The final value chosen for T is not without physical significance. It is indicative of the dynamics of the soil wetting and drying processes in the catchment.

4.2.3 Application Of Model To Magela Creek Data G.S.821008 to G.S.821009

For the section of Magela Creek between gauging stations G.S.821008 and G.S.821009, pluviograph data were available for 5 sites for the 1977/78 wet season. These 5 sites are not uniformly distributed throughout the catchment, and an averaging of the daily rainfall readings from all these sites would have given more weight to rainfall occurring in the downstream section of the reach. For this reason, the data from only three reasonably equally spaced pluviographs were averaged to obtain the input data for the rainfall runoff model. The three arbitrarily chosen sites were R821008(A), R821009(B) and R821009(A) (see Figure 13), and the average daily rainfall based on these sites is shown in Figure 14. Although this method of averaging is satisfactory for the preliminary modelling studies of this project, it is obviously crude and alternative procedures for obtaining representative rainfall, such as the Thiessen polygon method (Gilman, 1974, p.28) or a multi-input transfer function approach (Young and Whitehead, 1977) may have some advantages.

With this rainfall series as the input, a model was identified and estimated using the procedure outlined in Section 4.2.2. The output series to be modelled in this case was the difference between the observed hydrograph at gauging station G.S.821009 and the estimated flow from the flow routing model (see Figure 15a). This residual series was derived by subtracting the output of the deterministic flow routing model from the observed hydrograph at G.S.821009, and is shown in Figure 15b. In this case, a time-series model for the rainfall-runoff process was identified as being of a second order transfer function, zero time delay form; i.e.,

$$x_k = \frac{B(z^{-1})}{A(z^{-1})} \cdot u'_k \tag{22}$$

where z^{-1} is the backward shift operator,

i.e., $z^{-1}x_k = x_{k-1}$

while $A\left[z^{-1}\right] = 1 + a_1 z^{-1} + a_2 z^{-2}$

$B\left[z^{-1}\right] = b_0 + b_1 z^{-1}$

a_1, a_2, b_0, and b_1 are parameters to be estimated.

A large discrepancy between the estimated runoff, x_k, and the residual series of the flow routing model, shown in Figure 16, is evident on day 115. A close examination of the data about this time reveals that although little rain was received at Sites 8A, 9A and 9B, very heavy falls were recorded at the two pluviographs on the Ranger site. Data from these two sites were not included in the average rainfall calculation for the rainfall input series, and this explains the large apparant model error on day 115. It also indicates that a more sophisticated analysis (such as the methods previously referred to) may be appropriate and that a simple averaging process for rainfall data can lead to errors due to the heterogeneous nature of the rainfall distribution.

For the present illustrative purposes, however, the simple univariate analysis will be continued. A shortened data set was examined and the parameter values were:-

$a_1 = -0.42$

$a_2 = 0.36$

$b_0 = 1.31$

$b_1 = 1.33$

Thus the final 'black box' deterministic rainfall-runoff model is of the form:-

$$x_k = \frac{1.31\ z^{-1} + 1.33\ z^{-2}}{1 - 0.42\ z^{-1} + 0.36\ z^{-2}} \cdot u'_k + \xi_k \qquad (23)$$

It was not considered worthwhile developing an ARMA model for the residual noise series ξ_k in this instance, as the deterministic component is in need of further refinement especially in terms of improvement of the characterisation of bed infiltration and a and b parameter determination in the flow routing model, and also more suitable treatment of the available rainfall data as was suggested earlier. These modifications could be expected to reduce the rather large residual 'noise' series evident in Figure 16.

The inadequacy of this particular model is however, not only revealed by the poor fit to the 'observed' runoff series. An examination of the model's impulse response (Figure 17) which is directly equivalent to the unit hydrograph representation of traditional hydrological analysis, shows 'negative flows' on the recession limb of the hydrograph. Obviously this is not physically meaningful and is a first indication that the model is in need of modification.

A second indication is provided by examining the changes in the parameter values during the wet season. These time varying estimates provide a means of judging the efficiency of the seasonal adjustment of the data such as the modification of the input flow to the flow routing model to account for bank storage and the use of the short term filter to modify the input series to the rainfall-runoff model.

As an example of this procedure, the b_0 and b_1 parameters for the model of equation 23 are plotted in Figures 18a and 18b. It is clear that these parameter values still reflect some long term seasonal variation. Analysis of the time varying estimates in this way allows evaluation of different empirical data adjustment procedures (such as the low pass filter for the rainfall series). The most suitable procedure is the one which best transforms the resulting time series model into stationary (time-invariant) parameter form.

Transfer function models similar to that of equation 23 were estimated for the residual series resulting from the use of both the low pass filter and the short-term filter techniques with the flow routing model. A comparison of the residual 'noise' series in both cases indicated that the short-term filter technique may at least be as good as the low pass filter in characterising the bank storage process in the upper reaches of the Magela system.

4.3 TOTAL STREAM FLOW MODEL

As indicated in Figure 5, the final downstream hydrograph is derived by adding the output of the flow routing model and the rainfall-runoff model. Figure 19 shows the total streamflow model output at gauging station G.S.821009 based on an input flow at G.S.821008 which was modified using the short term filter technique. The difference between the model output and the observed data for this model is the residual 'noise' series from the rainfall-runoff model.

As has been explained, these models only represent an initial attempt at trying out the particular systems analysis techniques on Magela Creek data and are in need of further refinement and validation using streamflow data from other years before they could be confidently applied for the purposes of streamflow prediction. Further work along these lines could not be carried out in the present project, because data from the Magela Creek was not available until near the end of the project.

4.4 'BLACK BOX' FLOW MODEL.

It should be stressed that the choice of a particular streamflow modelling technique will be determined by many factors such as availability of data and the extent of knowledge of the hydrologic mechanisms involved. Also, and most importantly, the objectives of the study should be of primary consideration.

In the case of the Magela system, as has been noted previously, rainfall can be quite heterogeneously distributed even within small segments of the whole catchment. In these circumstances, it seems appropriate to account for rainfall-runoff effects separately to any basic flow routing model (as was done in Section 4.2) when the aim is to make predictions of streamflow downstream of the release point such as would be required for a water quality model.

There will, however, be other aspects of the water management program for which even simpler models could prove useful. It is suggested, for example, that contaminated water releases will be made under steady state or falling hydrograph conditions to minimise the possibility of flow into any 'back-flow' areas (Pancontinental, 1977, p.151). If this technique is adopted, it would be quite useful to have a simple model to provide advance notice of such conditions in order that releases may be suitably planned.

An example of a simple model which would enable hydrograph predictions of this sort to be made and which only requires quite minimal input data is a 'black box' model based on upstream flow measurements. 'Black box' models of this type were developed in this study for gauging station sites on the Magela Creek using 1974/75 data for a large flood event which occurred at the end of the wet season. The *CAPTAIN* package was used to identify and estimate a discrete time-series transfer function model in a way similar to that described in section 4.2.2 for rainfall/runoff, but on this occassion with the upstream flow as the input time series.

As an example of this approach, the flow at gauging station G.S.821009 was modelled using 6 hourly flow data at G.S.821008 as the input. The most suitable model in this case was identified as being of a first order form as follows:-

$$x_k = \frac{b_0 z^{-1} + b_1 z^{-2}}{1 + a_1 z^{-1}} \cdot x'_k$$

where x_k = downstream flow at G.S.821009

x'_k = upstream flow at G.S.821008

z^{-1} = backward shift operator

and a_1, b_o, b_1, are parameters to be estimated.

The choice of this particular model structure was made by using an instrumental variable technique developed by Yount *et al*, (1978). This approach is based on the assumption that a good model of time-series data is one which simultaneously provides a good fit to the data (i.e. a low *residual* estimation error variance) and possesses well-defined, low variance parameter estimates. A summary of the various model structures examined and their performance in relation to the previously mentioned criteria, is given in Appendix 2.

Estimation of the parameter values was carried out using the same iterative version of the IVAML algorithm referred to in Section 4.2.2. The final estimates obtained in this way, together with their estimated approximate standard errors (in parentheses) are as follows:-

a_1 =-0.24 (0.03)

b_0 = 0.56 (0.03)

b_1 = 0.61 (0.06)

In other words, the transfer function model between x_k and x'_k is:-

$$x_k = \frac{0.56\ z^{-1} + 0.61\ z^{-2}}{1 - 0.24\ z^{-1}} .\ x'_k$$

or

$$x_k = 0.24\ x_{k-1} + 0.56\ x'_{k-1} + 0.61\ x'_{k-2}$$

A comparison of the observed hydrograph at G.S.821009 and the estimated hydrograph using this model is given in Figure 20. It is worth noting the parametric efficiency or parsimony of this model which only required 3 coefficients for adequate characterisation.

This transfer function 'black box' model also enables a certain amount of physical interpretation. The steady state gain between gauging stations G.S.821008 and G.S.821009 may be computed from the model parameters and this indicates the proportion of the total flow at the downstream point which is due to rainfall-runoff processes between the two system boundaries.

In this case the steady state gain (SSG) is calculated from the equation:-

$$SSG = \frac{b_0 + b_1}{1 + a_1}$$

$$= 1.54$$

i.e., the flow at G.S.821009 exceeded the flow at G.S.821008 by approximately 50% due to rainfall-runoff processes between these system boundaries. Finally, it should be noted that the 'black box' model estimated here is based on a restricted data base; if the model was to be used in the manner suggested, then similar analyses should be carried out on a much larger data base to ensure that the model is consistent over reasonable periods of time. In other words, the previous analyses is provided here to exemplify the approach rather than provide a 'final' model.

CHAPTER 5

LONGITUDINAL DISPERSION MODEL/WATER QUALITY MODEL.

5.1 WATER QUALITY MODELLING - GENERAL

As described earlier (section 1.4), the water quality parameters which are of major concern in the Magela Creek system are heavy metal concentrations. A water quality model will be required to enable management decisions to be made regarding the timing and quantities of any contaminated water releases. The objective will be to ensure that heavy metal concentrations remain within acceptable levels within the Magela system and that, as far as possible, these contaminants are flushed out of the Magela system thus minimising the chance of any longer term adverse environmental effects. The water quality model needed for these purposes will require incorporation of a streamflow model since streamflow has considerable influence over the dynamic properties of the river and obviously affects its dilution and dispersion characteristics.

For the present project, it was desired to develop the simplest possible model consistent with reproducing the dilution and dispersion characteristics observed during the dye trace experiment in Magela Creek (See Chapter 3). In addition, the model needs to be a dynamic model capable of accepting time varying inputs of both river flow and effluent and operating upon them to give time varying output concentrations at downstream points in the river system. The model should also 'provide a reasonable mathematical approximation of the physico-chemical changes occurring in the river system and should be verified against real data collected from the river over an extended period of time'. (Young and Beck, 1974, p.456).

In relation to this latter point, the physico-chemical changes referred to would include any heavy metal losses due to mechanisms such as absorption on soils and uptake by various plants and animals. Whilst it is extremely important to be able to assess the level of this biological uptake and understand the mechanisms involved for the purpose of setting water quality standards, it is not necessary to attempt to include all these complex processes in the water quality model. Indeed, it would be foolhardy, especially in these initial stages, as there is a general paucity of information about these aquatic systems and specific data for the Magela system are very limited (Ranger Inquiry, 1977). Of course, if, as a result of further studies in the region, the various mechanisms controlling the fate of heavy metals were to become sufficiently well known, they could be incorporated in the model at that stage.

Although the conventional approach to modelling longitudinal dispersion is to consider a second order partial differential diffusion equation (Whitehead and Young, 1975), the simplest *a priori* model in this situation is probably one which is based on the conservation of mass over a reach of the river, and which allows for the possibility of sources and sinks within the reach.

This model could be made quite complex by the insertion of all the possible source and sink terms which the analyst feels *may* effect the system. But the incorporation of all these terms would be counter-productive, since only a few of them are likely to have a discernible effect on the observed variables and would thus be fully identifiable from the data (Young, 1977, p.17).

Verification of any water quality model against observed data could be carried out by using the model with data collected from radioactive and dye tracer experiments. In the case of dye traces, however, any verification can only be tentative as the behaviour of dyes, which are not conservative in the medium to long term, may not be directly comparable with that of heavy metals for which absorption and uptake characteristics are largely determined by physico-chemical form.

5.2 MODEL STRUCTURE

The basic structure of the model idealises each reach of the river as a plug flow reactor followed in series by one or more continuous stirred tank reactors (C.S.T.R.) (Figure 22).

The plug flow reactor is a zero order system in which no mixing is assumed to occur, and in which a pulse input, for example, appears unchanged in shape at the reactor exit but delayed by a time equal to the time constant or residence time (Td) of the reactor (Andrews, 1974, p.269).

The C.S.T.R. is a fundamental feature of many mechanistic models and it has been used in the modelling of biological processes of wastewater treatment and in modelling the dynamics of water quality in rivers (Beck, 1976; Andrews, 1974; Young and Beck, 1974). An ordinary differential equation C.S.T.R. model can be derived for contaminant concentration by considering a mass balance across the C.S.T.R:

$$V(t)\frac{dC_0(t)}{dt} = Q(t)C_i(t) - Q(t)C_0(t) + Q_e(t)C_e(t) - KC_0(t) \tag{24}$$

Accumulation rate	=	mass input rate	-	mass output rate	+	effluent mass input rate	-	loss rate

where $V(t)$ = volume of C.S.T.R.

$C_o(t)$ = downstream concentration

$C_i(t)$ = upstream concentration

$Q_e(t)$ = effluent discharge flow rate

$Q\ (t)$ = flow rate through reach

$C_e(t)$ = effluent discharge concentration

K = contaminant loss coefficient

t = time

When the flow rates and reactor volume are constant, the process can be classified as a first order linear system with constant coefficients. The solution of equation 24 in the form of a discrete time equation is given in Appendix 111.

Although the basic C.S.T.R. component of the model does not explicitly include mixing or dispersion terms, these effects are inherently contained within the exponential weighting of the equation solution. Different degrees of dispersion can be achieved with this basic model by placing different numbers of reactors (reaches) in series, in the same way that attenuation of the flood hydrograph was controlled by the number of reaches used in the flow routing model. Indeed, it will be noted that the equations are similar in both cases.

For short river segments it is sometimes possible to dispense with the plug flow reactor component as the lag properties associated with the C.S.T.R. model can adequately account for the pure time delay (e.g. Young and Beck, 1974).

5.3 APPLICATION OF MODEL TO MAGELA CREEK

In the case of the Magela Creek system, the model was applied to the simulation of an impulse input of dye at the injection point (see Figure 4). Dye concentrations at sites 1 and 2 were modelled, and the model output compared with the observed data. The river cross-sections at sites 1 and 2 were composed of three channels and, at both sites, water samples from each channel were analysed for dye concentration. Plate 6 shows the channelling at site 2 which was also the location of gauging station G.S.821009. For the purpose of modelling, the average dye concentration over the three channels at each site was selected as the observed data.

It was not found possible to adequately capture both the dispersion and transportation characteristics of the system with the C.S.T.R. representation alone, and a plug flow reactor component was required in conjunction with the C.S.T.R.

5.3.1 C.S.T.R. Model

In the circumstances where adequate data on the system is available and the a and b parameters characteristic of the river segment are known, then only N (number of reaches) can be varied in the attempt to simulate both the transportation and dispersion effects. In this instance, however, due to the uncertainty surrounding the appropriate values for the a and b parameters, there were three parameters: a, b and N.

PLATE 6 Gauging Station G.S.821009.

Site 2 for Dye Tracing Experiment.

The effect of varying N is shown in figure 23. As N increases, the transportation effect is increased and the dispersion effect is decreased. In the limit, as N becomes infinitely large, the series of C.S.T.R.'s approximates a plug flow reactor and produces a pure time delay with no dispersion effect.

In modelling the river segment just upstream of gauging station G.S.821009 from the injection point to site 2, the values chosen as a first estimate for a and b were 0.117 and 0.40 respectively. The selection of these particular values for a and b is described in section 4.1.2. The sensitivity of the modelled concentration profile to variations of $\pm$ 10% about these values of a and b is shown in figures 24 and 25 respectively. These figures indicate how changes in both dispersion and transportation result from changes in a and b parameter values.

A number of model outputs were computed with variations to all three parameters, a, b and N, and the best result, shown in Figure 26, occurred for N = 40, a = 0.117 and b = 0.4. This fit between estimated and observed concentration profiles is not good enough to justify the use of the C.S.T.R. model alone, and so a pure transportation lag in the form of a plug flow reactor prior to the C.S.T.R. was incorporated in the model.

5.3.2 Plug Flow Reactor In Series With C.S.T.R.

With this coupled series of reactors, it was possible to reproduce both the dispersion and transportation characteristics which were indicated by the dye tracer experiments. At site 2, for example, a three reach model with a pure time delay of 5.1 hours, and a and b parameter values of 0.146 and 0.3 respectively, produced a computed concentration profile almost identical with the observed data (see Figure 27).

Note that the flow rate at the time of the dye tracing experiment was determined from the concentration profile of a radioactive tritium tracer release which was made simultaneously with the dye release. The method and results of this flow calculation are outlined in Smith *et al*, (1978b, p.22).

At site 1, for this same flow rate, a two reach model with a pure time delay of 3.1 hours and slightly different a and b parameter values (a = 0.093, b = 0.4) also gave a quite acceptable fit to the data (see Figure 28). Some difference in the a and b parameter values used for modelling concentration profiles at sites 1 and 2 is to be expected as the hydraulic characteristics of these two river segments are different. Confirmation of the values chosen must however, await further tracing studies and these results can only be regarded as tentative at this stage.

It is quite encouraging to note that there seemed to be a relationship between the pure time delay (Td) and the total time constant for the river segment (Tt) such that:-

$$\frac{Td}{Tt} = \theta \qquad (25)$$

where θ = a constant

This relationship was suggested from the estimated concentration profiles of Figures 27 and 28 for which the

values of Td/Tt were 0.72 and 0.70 respectively.
With the combined system of Plug flow reactor and C.S.T. R's, the Total time constant over the river segment is the sum of the pure time delay and the time constant associated with the series of C.S.T.R.'s.
i.e.

$$Tt = Td + \frac{l.N}{v} \tag{26}$$

or

$$Tt = Td + \frac{l.N}{aQ^b} \tag{27}$$

where l = length of each reach

N = number of reaches (model order)

It might be expected that this combined system of plug flow reactor and C.S.T.R. would introduce a difficulty in determining an appropriate Td, since all these terms in equation 26 are time-varying and dependent on the flow rate. As discharge increases, for example, both Tt and $\frac{l}{v}$ decrease. If, however, the relationship of Equation 25 is confirmed by further studies, then a convenient method of determining the pure time delay component required in the model becomes apparant:-

If the relationships of equations 25 and 27 are combined, then:

$$\frac{Td}{\theta} = Td + \frac{l.N}{aQ^b} \tag{28}$$

or

$$Td = \frac{l.N}{aQ^b}\left[\frac{\theta}{1-\theta}\right] \tag{29}$$

If it were possible to empirically determine a value of for each river segment, then equation 29 would define the relationship between Td and Discharge Q.

Although there was not time in the present project, it is clearly a simple matter to introduce a time-varying flow rate into the water quality model and thus simulate the actual dynamic conditions prevailing in the river.

CHAPTER 6

CONCLUSIONS

The problems associated with the development of a scheme for the management and control of contaminated water releases from the proposed uranium mines into a complex and uncertain system such as the Magela Creek are indeed manifold. This project has only focused on one of these problems; namely, the development of suitable streamflow and water quality models. When sufficiently developed, such models will, undoubtedly, assist in both the determination of appropriate release strategies and water quality standards and then the subsequent planning of any releases once mining operations are underway.

Due to time constraints and lack of adequate streamflow and rainfall data until very late in the course of this project, it was not possible to attempt anything more than very preliminary modelling of streamflow for the Magela Creek. Fortunately, the models which were developed were intentionally kept as simple as possible and so their data requirements were relatively small. Even so, data was insufficient for some purposes and, consequently, it was necessary to estimate many of the parameters required in a rather crude fashion.

The exercise of modelling does, however, provide a systematic way of appraising the available data and often reveals information on the system which is not made apparant by more simple analysis of the data. The models can also be useful in assessing future data requirements and in indicating the type of field exercises most suitable for this data collection. If, for example, it was intended to continue the development of the models used in this project, more exact definition of the a and b parameters used in the relationship $v = aQ^b$ (equation 6) would be required for the specific river segments of interest. This could be achieved by a series of further tracing studies, similar to that described in Chapter 3, for different river segments under a range of discharge conditions.

On the basis of the limited streamflow modelling undertaken in this project, it would seem that the simple, highly aggregated model which was used certainly merits further development in order to assess its suitability for application to the Magela system. Although the modelling results obtained to date could only be considered preliminary further refinements could be expected to enhance the predictive ability of the model. These would include improvements in the characterisation of the bank storage effect, more exact identification of appropriate a and b parameter values by field experiments, and better handling of the rainfall data as input to the rainfall-runoff model by either the use of a more sophisticated averaging process such as Thiessen polygons or by multivariable systems analysis. After such modifications, the model would need to be validated against data which was not used in the identification and estimation procedures.

In this project, only the river segment upstream of gauging station G.S.821009 was modelled using the total streamflow model. The characteristics of this section of the Magela system are not unlike those for which this modelling approach has been successfully applied elsewhere. Downstream sections of the Magela, which include billabongs and floodplain obviously present very different and unique problems, and at this stage, it is not possible to comment on the suitability of the models developed in this project for application in this part of the Magela system. An example of the difficulties in characterising streamflow in these lower reaches is afforded by the complex loop rating curve for gauging station G.S.821017 (Figure 29a) which contrasts quite markedly with the more typical rating curve of G.S.821009 (Figure 29b).

The simple ordinary differential equation compartmental model which was used for modelling longitudinal dispersion and was based on mass conservation over the compartments (reaches) of the river, appears, at this stage, quite promising as a basis for a water quality model, at least in the upper reaches of the Magela system. Validation of this model would also be required and the model's applicability to the downstream sections of the Magela system need to be assessed. These two requirements could be readily met by using data from other tracing studies. If it is confirmed that the plugflow component is a necessary part of the model as was indicated in section 5.3, further development work would be required to overcome the potential problems of the time-varying transportation lag of the plugflow reactor which is associated with a variable discharge. A possible solution could be provided if the relationship of equation 25 suggested in section 5.3.2 is verified by application of the model to other data.

It has been emphasised that this study only represents the initial stages in the assessment of these models, and their suitability as a basis for managing the release of contaminated water to the Magela Creek can only be determined by further investigation. Models of this type are considered to be of great practical utility in systems analysis aimed at solving control and management problems (Young *et al*, 1978a) and if, when developed further, they are found to adequately characterise the streamflow and dispersion behaviour of the Magela system, they should prove to be useful in contending with the problem of contaminated water releases to the Magela Creek.

APPENDIX 1

DERIVATION OF PARAMETER a

For the assumptions of a wide rectangular channel and a mean flow velocity approximately equal to wave celerity, Whitehead *et al* (1978a, p.24-26) derive relationships for a and b based on the hydraulic reach characteristics by consideration of the Manning's equation and the Kleitz-Seddon principle.

These relationships are:-

$$b = 0.4 \qquad \text{(A1)}$$

and
$$a = \frac{S^{(1-b)/2}}{(1-b)n^{(1-b)}B^{b}} \qquad \text{(A2)}$$

where S = bottom slope

n = Manning's roughness coefficient

B = channel width

For the section of Magela Creek between the injection point and site 2 (see figure 4), values for S, n and B were chosen as follows:-

S = 0.0007: derived from the longitudinal section diagram-Magela Creek Plains in Northern Territory Department of Transport and Works,(1978).

n = 0.055 : selected from channel type 'streams on plains' intermediate between 0.040 for 'clean, winding, some pools and shoals' and 0.070 for 'sluggish reaches, weedy, deep pools'. (Gregory and Walling, 1973, p.129).

B = 265m : determined from the cross-section diagram through the Magela Creek at the proposed discharge point (Ranger Uranium Mines Pty. Ltd., Ranger Project) at the high flow level of 200 m^3/s. This high flow level was selected as experience and has shown that parameters selected under these conditions produce reliable predictions for a wide range of flows(Whitehead *et al*, 1978a, p.7).

So
$$a = \frac{0.0007^{0.3}}{0.6 \times 0.055^{0.6} \times 265^{0.4}}$$
$$= 0.116$$

APPENDIX 11

MODEL STRUCTURE IDENTIFICATION

A comprehensive identification procedure is outlined in Young *et al*, (1978b) in which the final selection of a model is determined by consideration of both the 'goodness of fit' to the data and the variance of the parameter estimates. They propose using the average of the variance - covariance matrix of the estimated errors (EVN) for assessing the latter criteria and the total correlation coefficient R_T^2 for assessing 'goodness of fit',

where (i)

$$\text{EVN }(n) = \frac{1}{2\hat{n}+1} \sum_{i=1}^{2\hat{n}+1} \hat{P}_{ii} \qquad \text{(A3)}$$

and $\hat{n}$ is the estimated order of the system

and P_{ii} is the ith diagonal element of the $\hat{P}$ matrix (the estimated error covariance matrix)

and (ii) the total correlation coefficient is defined as

$$R_T^2 = 1 - \frac{J_0}{\sum_{k=1}^{N} Y_k^2} \qquad \text{(A4)}$$

where J_0 is the sum of the squares of the residuals

N is the total number of samples of the data set

Y_k is the observed output series.

If the model provides a good fit to the data (i.e. J_0 is small in relation to $\sum Y_k^2$, then the values of R_T^2 should be close to unity. Normally, the model structure selected is the one which yields the minimum EVN and has an acceptable model fit as determined from the R_T^2 value.

In the case of the 'black box' flow model of Section 4.4, the structure of the models which seemed to be possible candidates and their associated ln EVN and R_T^2 values are listed in table A1. All these models have a time delay of 1 sampling instant (6 hours).

TABLE A1

MODEL STRUCTURE	NUMBER OF a PARAMETERS	NUMBER OF b PARAMETERS	ln EVN	R_T^2
1	1	1	-6.98	0.985
2	1	2	-6.28	0.994
3	2	1	-6.16	0.991
4	2	2	-5.13	0.994

Of the models listed in table A1, all show very good fit to the data as evidenced by the high value of R_T^2. The last model (structure 4) can be eliminated on the basis of its larger EVN, and the model structure 3 can be eliminated by reference to its impulse response (equivalent to the unit hydrograph) which exhibits quite unacceptable behaviour by having slight negative values (equivalent to 'negative' flows on the recession limb of the hydrograph) (see Figure 21). It will also be observed in Figure 21 that both model structures 1 and 2 have typical impulse responses and are hence acceptable in a 'physical' sense. Model structure 2 was selected from these remaining two possibilities, with its slightly better fit being obtained at the expense of a somewhat inferior EVN value. But there is clearly little to choose between models 1 and 2.

APPENDIX 111

DERIVATION OF DISCRETE TIME EQUATION (WITH DECAY AND EFFLUENT ADDITION)

The continuous form of the C.S.T.R. model equation is:-

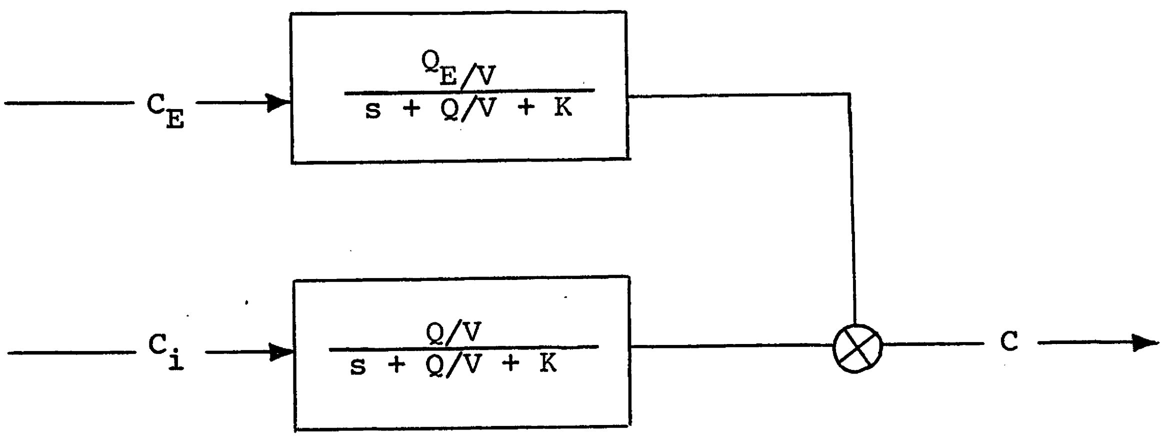
$$\frac{dC}{dt} = -\frac{Q}{V} C - KC + \frac{Q}{V} C_i + \frac{Q_E}{V} C_E \tag{A5}$$

using s notation

$$(s + Q/V + K)C = \frac{Q}{V} C_i + \frac{Q_E}{V} C_E$$

$$C = \frac{Q/V}{s + Q/V + K} C_i + \frac{Q_E/V}{s + Q/V + K} C_E \tag{A6}$$

Note: The block diagram representation is



If assumed that C_i and C_e are constant during the sampling interval, then Equation A2 is now solved by methods of Laplace transforms (See Coughanowr and Koppel, 1965, p.13-21) giving:-

$$C_k = e^{-(Q/V + K)\tau} C_{k-1} + \frac{Q/V}{Q/V + K}\left[1 - e^{-(Q/V + K)\tau}\right] C_{i_{k-1}} + \frac{Q_E/V}{Q/V + K}\left[1 - e^{-(Q/V + K)\tau}\right] C_{E_{k-1}} \tag{A7}$$

BIBLIOGRAPHY

ANDREWS, J.F. 1974 'Dynamic Models and Control Strategies for Wastewater Treatment Processes'. *Water Research.* 8: 261-289.

AUSTRALIA Department of Northern Territory 1973 *Report on Flooding of the Magela Creek in March, 1973.* Water Resources Branch. Hydrographic Section.

AUSTRALIA Northern Territory Department of Transport and Works 1978 *Uranium Province Hydrology.*

AUSTRALIA 1977 *Ranger Uranium Enviromental Inquiry Second Report.* Canberra: Australian Government Publishing Service.

AUSTRALIAN WATER RESOURCES COUNCIL, 1974. *Australian Representative Basins Programme - Progress 1973.* Hydrological Series Number 8. Canberra: Department of the Environment and Conservation.

BECK, M.B. 1976 'Dynamic Modelling and Control Applications in Water Quality Maintenance'. *Water Research.* 10: 575-595.

BISWAS, A.K. 1975 'Mathematical Modelling and Environmental Decision-making'. *Ecological Modelling. 1: 31-48.*

BOUGHTON, W.C. 1966 'A Mathematical Model for Relating Rainfall to Runoff with Daily Data'. *Civil Engineering Transactions, I.E. Aust.* C.E.8: 83-93.

CALKINS, D and DUNNE, T, 1970 'A salt Tracing Method for Measuring Channel Velocities in Small Mountain Streams'. *J. of Hydrology.* 11: 379-392.

CHOW, V.T., (ed.) 1964 *Handbook of Applied Hydrology.* New York: McGraw-Hill.

CHRISTIAN, C.S. and ALDRICK, J.M. 1977 *Alligator Rivers Study: A Review Report of the Alligator Rivers Region Environmental Fact-finding Study.* Canberra: Australian Government Publishing Service.

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION, 1969 *Lands of the Adelaide-Alligator Area, Northern Territory.* C.S.I.R.O. Land Research Series Number 25. Melbourne C.S.I.R.O.

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION 1976 *Lands of the Alligator Rivers Area Northern Territory*. C.S.I.R.O. Land Research Series Number 38. Melbourne: C.S.I.R.O.

CONWAY, N.F., DAVY, D.R., GILES, M.S., NEWTON, P.J.F. AND POLLARD, D.A. 1977 *The Alligator Rivers Area Fact-finding Study: Four A.A.E.C. Reports*. Lucas Heights: Australian Atomic Energy Commission Research Establishment.

COUGHANOWR, D.R. AND KOPPEL, L.B. 1965 *Process Systems Analysis and Control*. New York: McGraw-Hill.

CRAWFORD, N.H. AND LINSLEY, R.K. 1966 'Digital Simulation in Hydrology. Stanford Watershed Model IV'. *Technical Report number 39*. Stanford University: Department of Civil Engineering.

DAVY, D.R. 1973 'Environmental Studies for Uranium Provinces-Aims and Methods'. Proceedings of the A.A.E.C. Symposium on Environmental and Radiological Safety Aspects of the Mining and Processing of Uranium: IV/1-23. Lucas Heights.

DAVY, D.R. AND CONWAY, N.F. 1974. 'Environmental Studies: N.T. Uranium Province 1971/73. In Conway *et al*,. *The Alligator Rivers Area Fact-finding Study: Rour A.A.E.C. Reports*. 111/1-67. Lucas Heights: Australian Atomic Energy Commission Research Establishment.

DINCER, T. 1967 'Application of Radiotracer Methods in Streamflow Measurements'. In I.A.E.A., *Isotopes in Hydrology*. Vienna: I.A.E.A.

DUNIN, F.X. 1975 'Use of Physical Process Models'. In T.G. Chapman and F.X. Dunin, *Prediction in Catchment Hydrology*: 277-291. Canberra: Australian Academy of Science.

FISCHER, H.B. 1972 'A Lagrangian Method for predicting Pollutant Dispersion in Bolinas Lagoon, Marin County, California'. *U.S. Geol. Survey Prof. Paper 582-B*.

GARRICK, M., CUNNANE, C AND NASH, J.E. 1978 'A Criterion for Efficiency for Rainfall-Runoff Models. *J. of Hydrology*. 36: 375-381.

GILES, M.S. 1974 'Toxicity Studies on Aquatic Oranisms and Grass-Sedge Communities in the Magela Creek Area'. In Conway *et al.*, *The Alligator Rivers Area Fact-Finding Study: Four A.A.E.C. Reports*: 11/1-15. Lucas Heights: Australian Atomic Energy Commission Research Establishment.

GILMAN, C.S. 1964 'Rainfall" In V.T. Chow, *Handbook of Applied Hydrology*. New York: McGraw-Hill.

GREGORY, K.J. and WALLING, D.E. 1973 *Drainage Basin Form and Process: A Geomorphological Approach*. London: Edward Arnold.

HIMMELBLAU, D.M. and YATES, R.V. 1968 'A New Method of Flow Routing'. *Water Resources Research*. 4: 1193-1199.

LAURENSON, E.M. 1962 'Hydrograph Synthesis by Runoff Routing' *Water Res. Lab. Univ. of N.S.W. Report Number 66*.

LAURENSON, E.M. 1978 'Flood Routing Method'. In A. Pattison, *Australian Rainfall and Runoff*: 91-95. Australia: Institution of Engineers.

LEOPOLD, L.B. and MADDOCK T. 1953 'The Hydraulic Geometry of Stream Channels and some Physiographic Implications'. *U.S. Geol. Survey Prof. Paper 252*.

LEOPOLD, L.B. and MILLER, J.P. 1956 'Ephemeral Streams-Hydraulic Factors and their Relation to the Drainage Net'. *U.S. Geol. survey Prof. Paper 282-A*.

LEOPOLD, L.B., WOLMAN, M.G. and MILLER, J.P. 1964 *Fluvial Processes in Geomorphology*. San Fransisco: W.H. Freeman.

McALPINE, J.R. 1976 'Climate and Water Balance'. In R. Story *et al*, *Lands of the Alligator Rivers Area, N.T.*: 35-49. Land Research Series Number 38. Melbourne: Commonwealth Scientific and Industrial Research Organisation.

MEIN, R.G. 1977 Mathematical Modelling of Catchments. Proceedings of Institute of Engineers, Hydrology Symposium. Brisbane.

MEIN, R.G. and BROWN, B.M. 1976 Statistical Sensitivity of Parameters in a Rainfall-Runoff Model. Proceedings of Institute of Engineers, Hydrology Symposium, Sydney.

NASH, J.E. 1976 'Summary Report of "Workshop of Deterministic Models"'. *Hydrol. Sc. Bull.* 21:215-218.

PANCONTINENTAL MINING LTD. 1977 *The Jabiluka Project: Draft Environmental Impact Statement.* Sydney: Pancontinental Mining Ltd.

PATTISON, A and McMAHON, T.A. 1973 'Rainfall-Runoff Models using Digital Computers'. *Civ. Eng. TRans. I.E. Aust.* C.E. 15:1-4.

PILGRIM, D.H. 1976 'Travel Times and Nonlinearity of Flood Runoff from Tracer Measurements on a Small Watershed'. *Water Resources Research.* 12:487-496.

PILGRIM, D.H. 1977 'Isochrones of Travel Time and Distribution of Flood Storage from a Tracer Study on a Small Watershed'. *Water Resources Research.* 13:587-595.

PORTER, J.W. and McMAHON, T.A. 1971 'A Model for the Simulation of Streamflow Data from Climatic Records'. *J. of Hydrology.* 13: 297-324.

PRICE, R.K. 1975 Flood Routing Studies. *Flood Studies Report, VIII.* Nat. Environ. Res. Council. London: Whitefriars Press.

RANGER URANIUM MINES PTY. LTD. 1975 *Environmental Impact Statement February, 1974 and Supplements No. 1 and No. 2 May, 1975.*

SITTNER, W.T. 1976 'W.M.O. Project on Intercomparison of Conceptual Models used in Hydrological Forecasting'. *Hydrol. Sc. Bull* 21:203-213.

SMART, P.L. and LAIDLAW, I.M.S. 1977 'An Evaluation of Some Florescent Dyes for Water Tracing'. *Water Resources Research.* 13: 15-33.

SMART, P.L. and SMITH, D.I. 1976 'Water Tracing in Tropical Regions: The Use of Fluorometric Techniques in Jamaica'. *J. of Hydrology.* 30:179-195.

SMITH, D.I., YOUNG, P.C. and GOLDBERG, R.J. 1978a 'Provisional Summary Report of the Magela Creek Dye Tracing Experiments, March, 1978'. *CRES Working Paper AS/WP5.* Canberra: Centre for Resource and Environmental Studies, A.N.U.

SMITH, D.I., YOUNG, P.C. and GOLDBERG, R.J. 1978b 'Fluometric Dye Studies on the Magela Creek System, 13-20 March 1978'. Report prepared for the Office of the Supervising Scientist. Canberra: Centre for Resource and Environmental Studies, A.N.U.

SOUTHERN, R.L. 1966 'A Review of Weather Disturbances Controlling the Distribution of Rainfall in the Darwin-Katherine Region, N.T.'. *Bureau of Meteorology Working Paper 65-3203*. Melbourne: Director of Meteorology.

SUGAWARA, M., OZAKI, E., WATANAGE, I. and KATOUYAMA, Y, 1974 'Tank Model and its Applications to Bird Creek, Wollombi Brook, Bilkim River, Kitsu River, Sanaja River and Nam Mune'. *National Research Centre for Disaster Prevention Research Note Number 11*. Tokyo.

TODINI, E. and WALLIS, J.R. 1974 'Using C.L.S. for Daily or Longer period Rainfall-Runoff Modelling'. *Workshop on Mathematical Models in Hydrology*. Pisa, Italy.

VANSTEENKISTE, G.C. 1976 'System Simulation in the Testing Role'. In G.C. Vansteenkiste, *System Simulation in Water Resources*. Amsterdam: North Holland.

VENN, M.W. and DAY, B. 1977 CAPTAIN (Computer Aided Procedure for Time Series Analysis and the Identification of Noisy Processes) User Manual. *Report Number 39*. Oxon: Institute of Hydrology.

WATERCRES 1978 'Study of Water Quality in the Lower Molonglo Murrumbidgee Burrinjuck Region of the A.C.T. and N.S.W.'. 1st Progress Report, December, 1977. *CRES REPORT AS/R19*. Canberra: Centre for Resource and Environmental Studies, A.N.U.

WEEKS, W.D. 1977 'Rainfall-Runoff Modelling: 'Black Box' or 'Process'. Proceedings of Institute of Engineers Hydrology Symposium. Brisbane.

WEINMANN, P.E. and LAURENSON, E.M. 1977 Modern Methods of Flood Routing. Proceedings of Institute of Engineers, Hydrology Symposium. Brisbane.

WHITEHEAD, P.G. and YOUNG, P.C. 1975 'A Dynamic-Stochastic Model for Water Quality in Part of the Bedford-Ouse River System'. In G.C. Vansteenkiste, *Modelling and Simulation of Water Resource Systems*: 417-438. Amsterdam: North Holland.

WHITEHEAD, P.G., HORNBERGER, G. AND BLACK, R. 1978a 'Effects of Parameter Uncertainty in a Flow Routing Model'. *CRES Report AS/R25*. Canberra: Centre for Resource and Environmental Studies, A.N.U.

WHITEHEAD, P.G., YOUNG, P.C. and MICHELL, P.A. 1978b Some Hydrological and Water Quality Modelling Studies in the A.C.T. Region. Proceedings of Institute of Engineers, Hydrology Symposium, Canberra.

WHITEHEAD, P.G., YOUNG, P.C. and HORNBERGER, G. 1978c 'A Systems Model of Stream Flow and Water Quality in the Bedford-Ouse River. Part 1. Stream Flow Modelling'. *CRES REPORT AS/R10*. Canberra: Centre for Resource and Environmental Studies, A.N.U.

WILSON, J.F. 1968 'Fluorometric Procedures for Dye Tracing'. *Techniques of Water Resource Investigations of the U.S. Geol. Survey. Vol. 3, 31p.*

WOLMAN, M.G. 1955 'The Natural Channel of Brandywine Creek, Pennsylvannia'. *U.S. Geol. Survey Prof. Paper 271.*

WORLD METEOROLOGICAL ORGANISATION 1975 'Intercomparison of Conceptual Models used in Operational Hydrological Forecasting'. *W.M.O. Operational Hydrology Report Number 7.* Geneva. Switzerland.

YOTSUKURA, N. FISCHER, H.B. and SAYRE, W.W. 1970 'Measurement of Mixing Characteristics of Missouri River between Sioux City, Iowa and Plattsmouth, Nebraska'. *U.S. Geol. Survey Water Supply Paper 1899G.*

YOUNG, P.C. 1974 'Recursive Approaches to Time-Series Analysis'. *Bulletin Inst. of Maths and its Applications. 10: 209-224.*

YOUNG, P.C. 1977 'A General Theory of Modelling for Badly Defined Systems'. *CRES Report AS/R9;* to appear in G.C. Vansteenkiste, *Modelling and Simulation of Land, Air and Water Resources Systems.* Amsterdam/New York: North Holland/ American Elsevier.

YOUNG, P.C. and BECK, M.B. 1974 'The Modelling and Control of Water Quality in a River System'. *Automatica.* 10: 455-468.

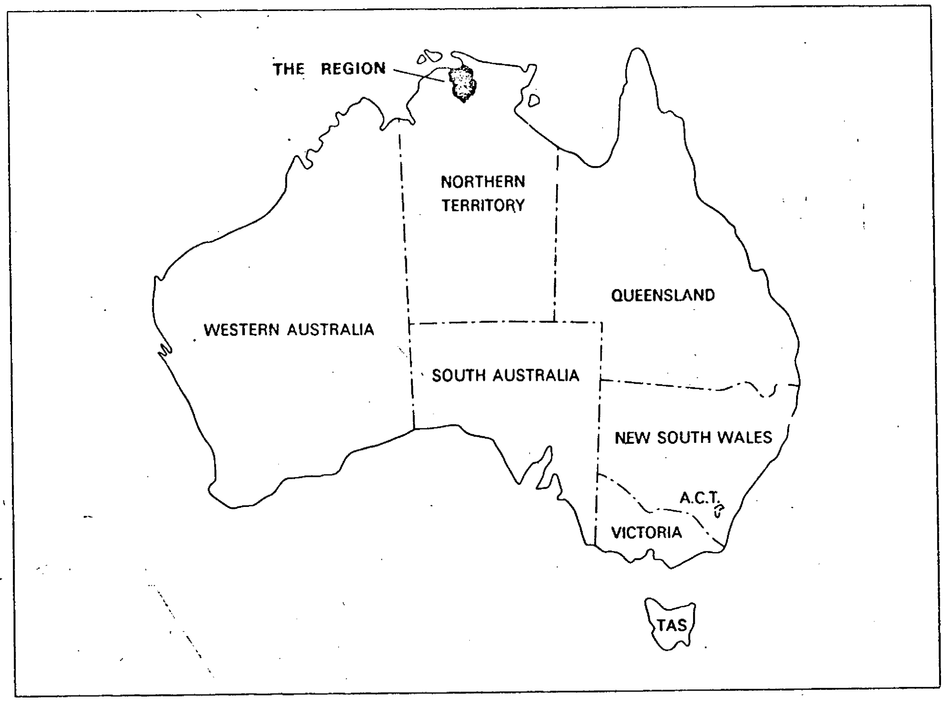
YOUNG, P.C., HORNBERGER, G. and SPEAR, R. 1978a 'Modelling Badly Defined Systems: Some further Thoughts. *Proceedings of SIMSIG-78: Simulation Conference.* Simulation Modelling Techniques and Applications Canberra: 24-32.

YOUNG, P.C., SHELLSWELL, S.H. and NEETHLING, C.G. 1971 *Report No. CUED/B-Control/TR16.* Dept. of Engineering. University of Cambridge.

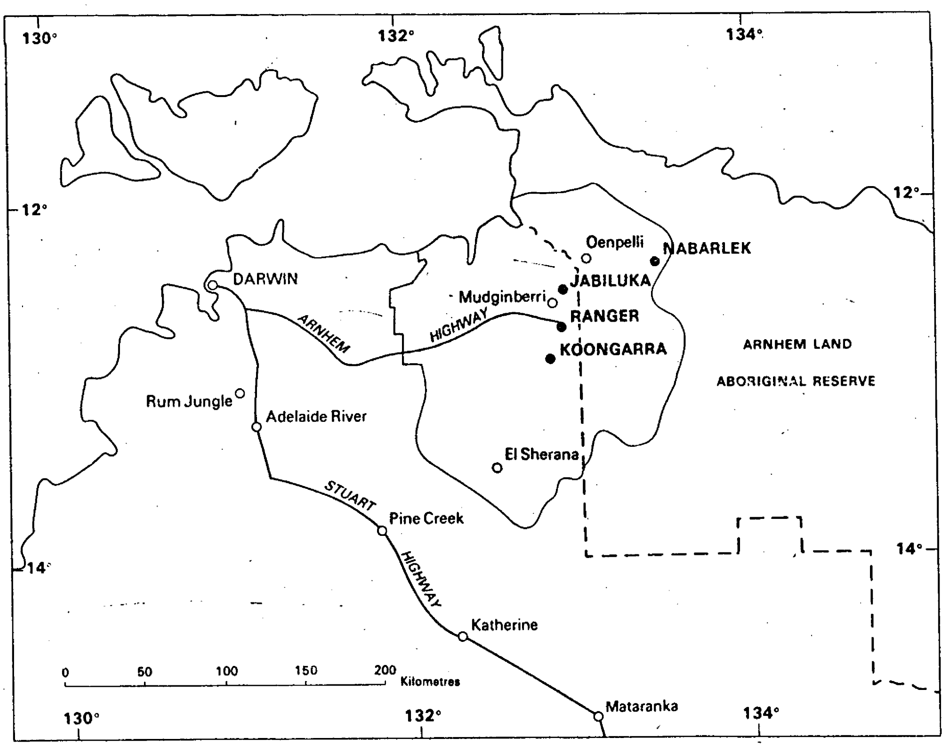
YOUNG, P.C., JAKEMAN, A. and McMURTRIE, R. 1978b 'An Instrumental Variable Method for Model Structure Identification'. *CRES Report AS/R22.* Canberra Centre for Resource and Environmental Studies, A.N.U.

YOUNG, P.C. and WHITEHEAD, P.G. 1977 'A Recursive Approach to Time-Series Analysis for Multivariable Systems'. *Int. J. of Control.* 25:457-482.

ALLIGATOR RIVERS REGION & MINE SITES



Location Maps



(from: Ranger Uranium Environ. Inquiry, 2nd Rep.)

FIG. 1

(from; Ranger Uran. Environ. Inquiry, 2nd Rep.)

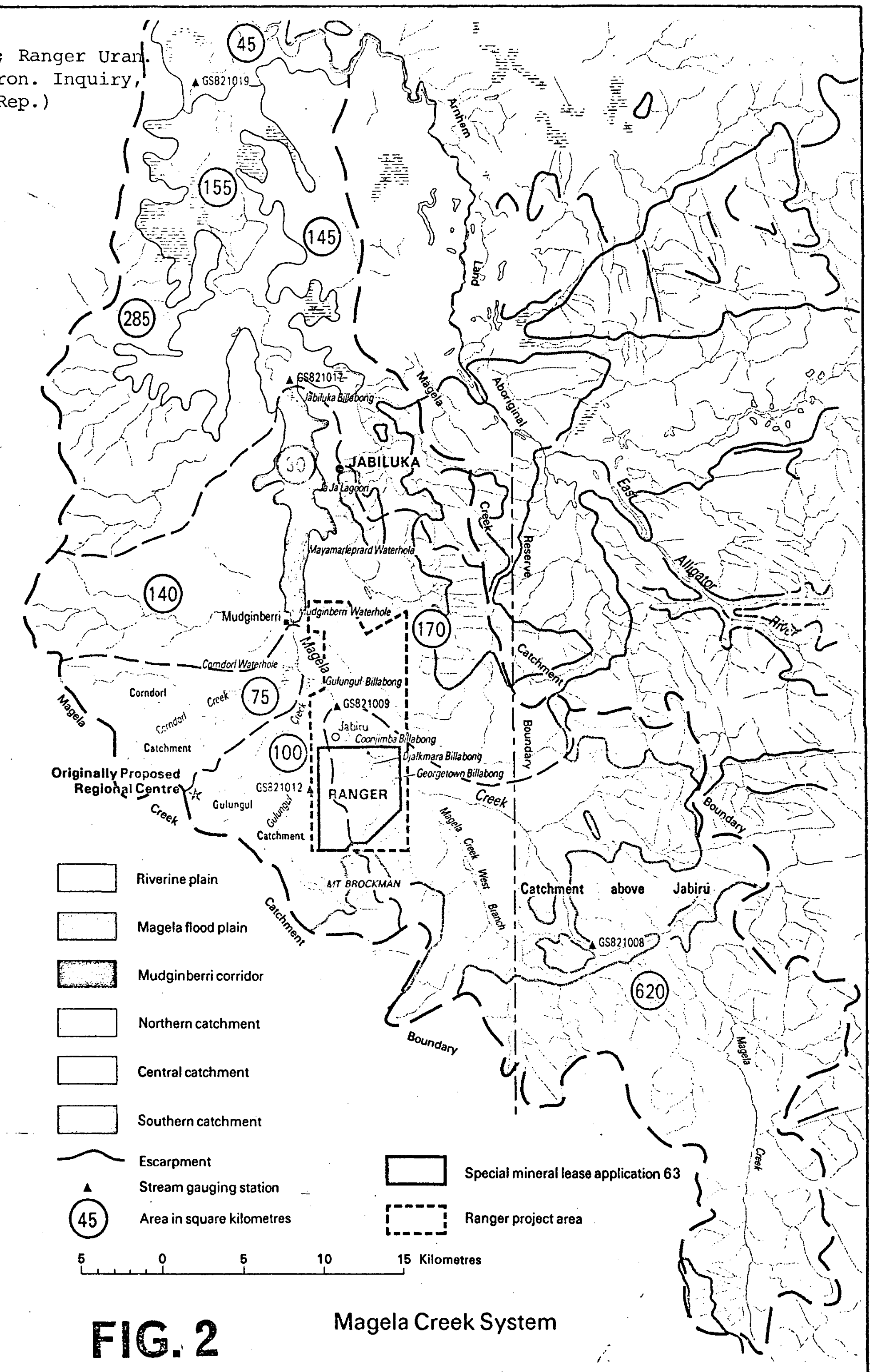
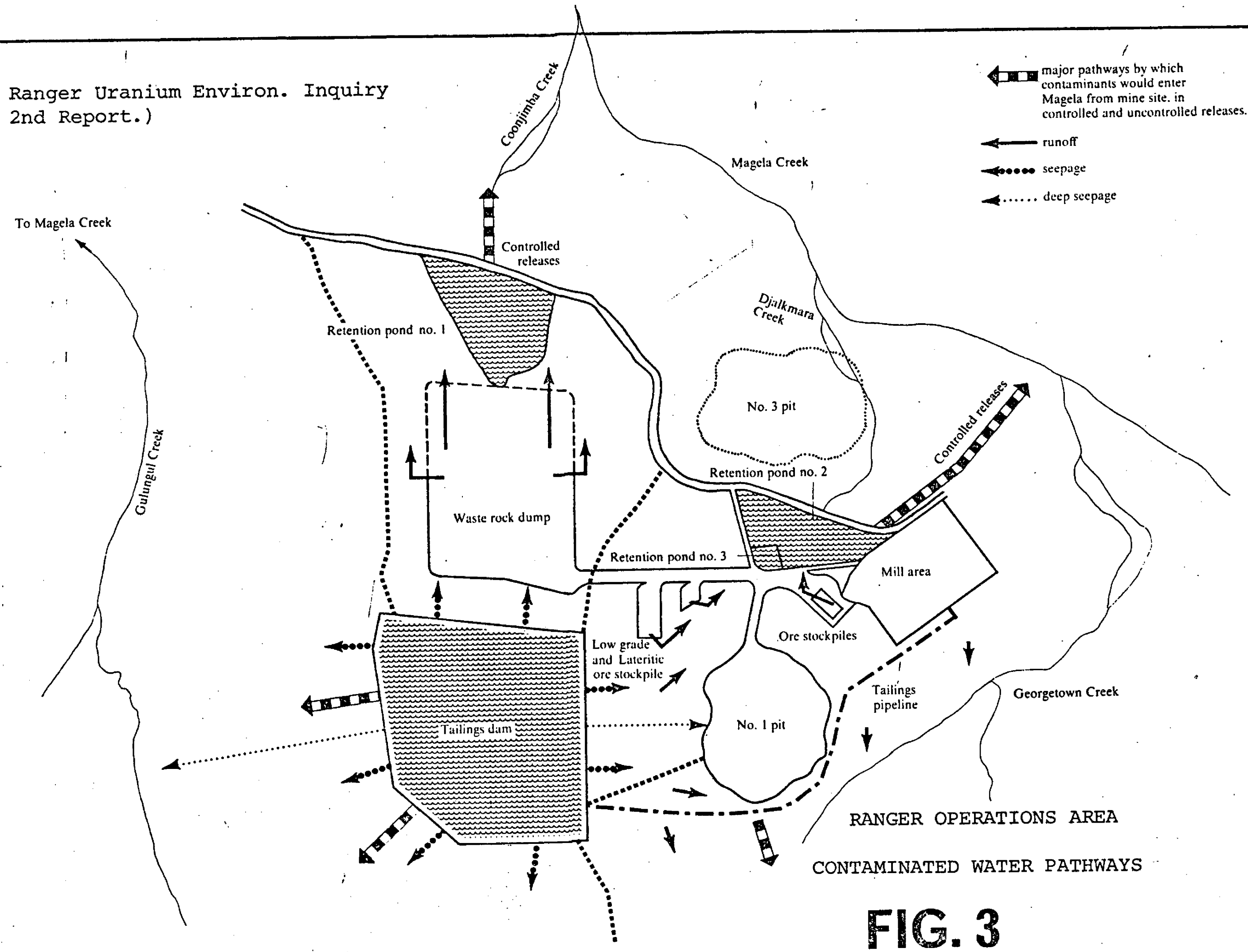


FIG. 2 Magela Creek System

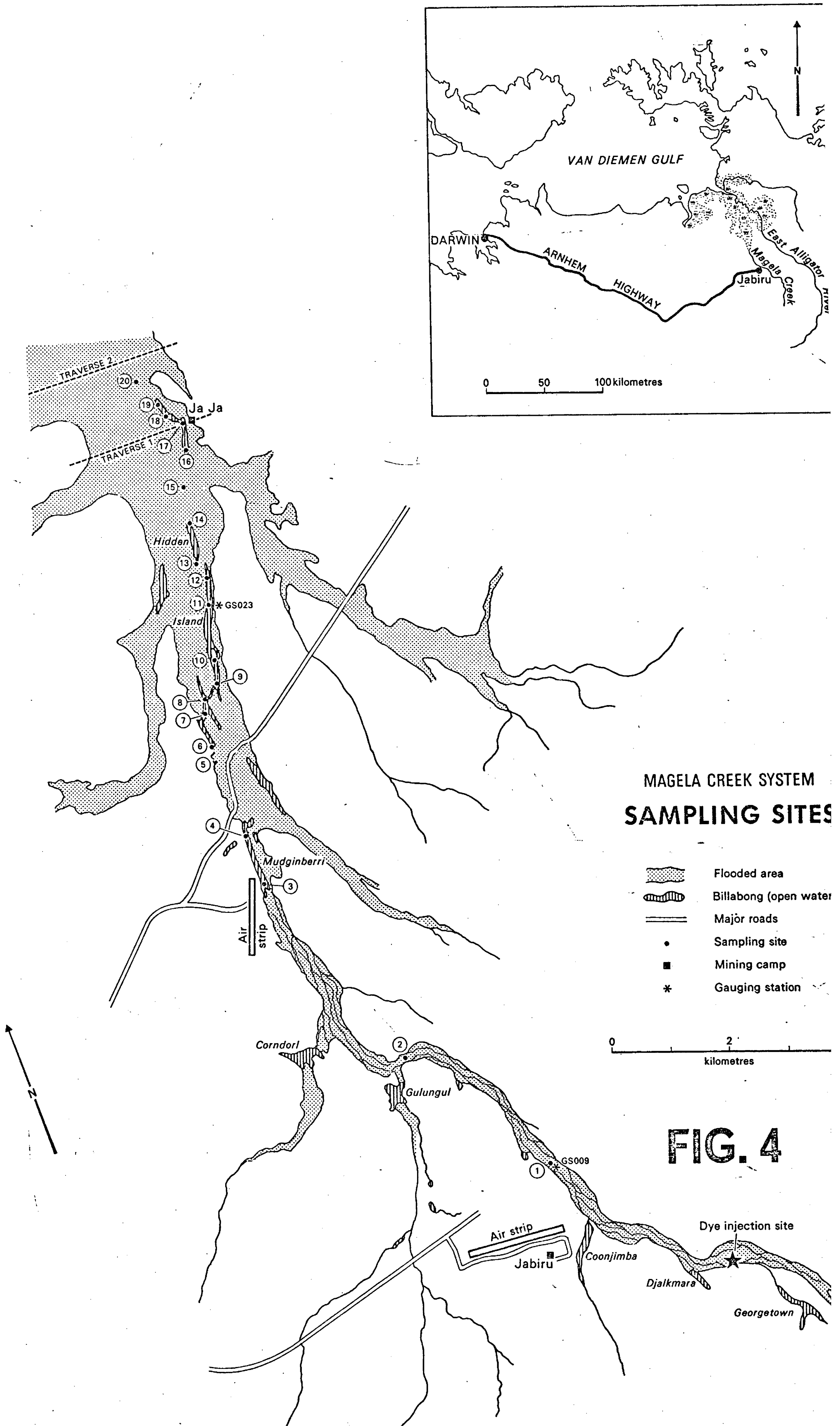
(from: Ranger Uranium Environ. Inquiry
2nd Report.)



RANGER OPERATIONS AREA

CONTAMINATED WATER PATHWAYS

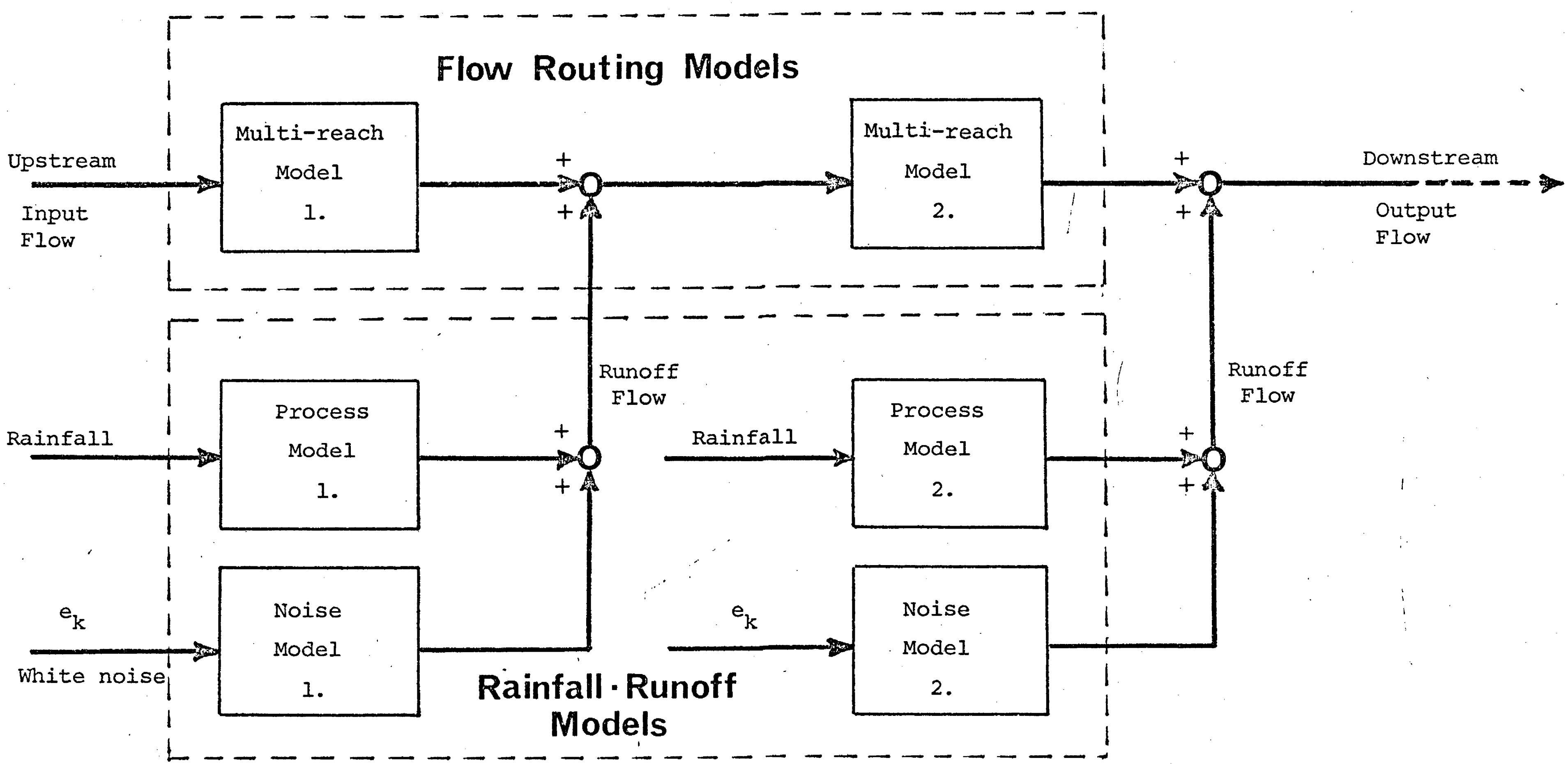
FIG. 3



MAGELA CREEK SYSTEM

SAMPLING SITES

FIG. 4



TOTAL STREAMFLOW MODEL

FIG. 5

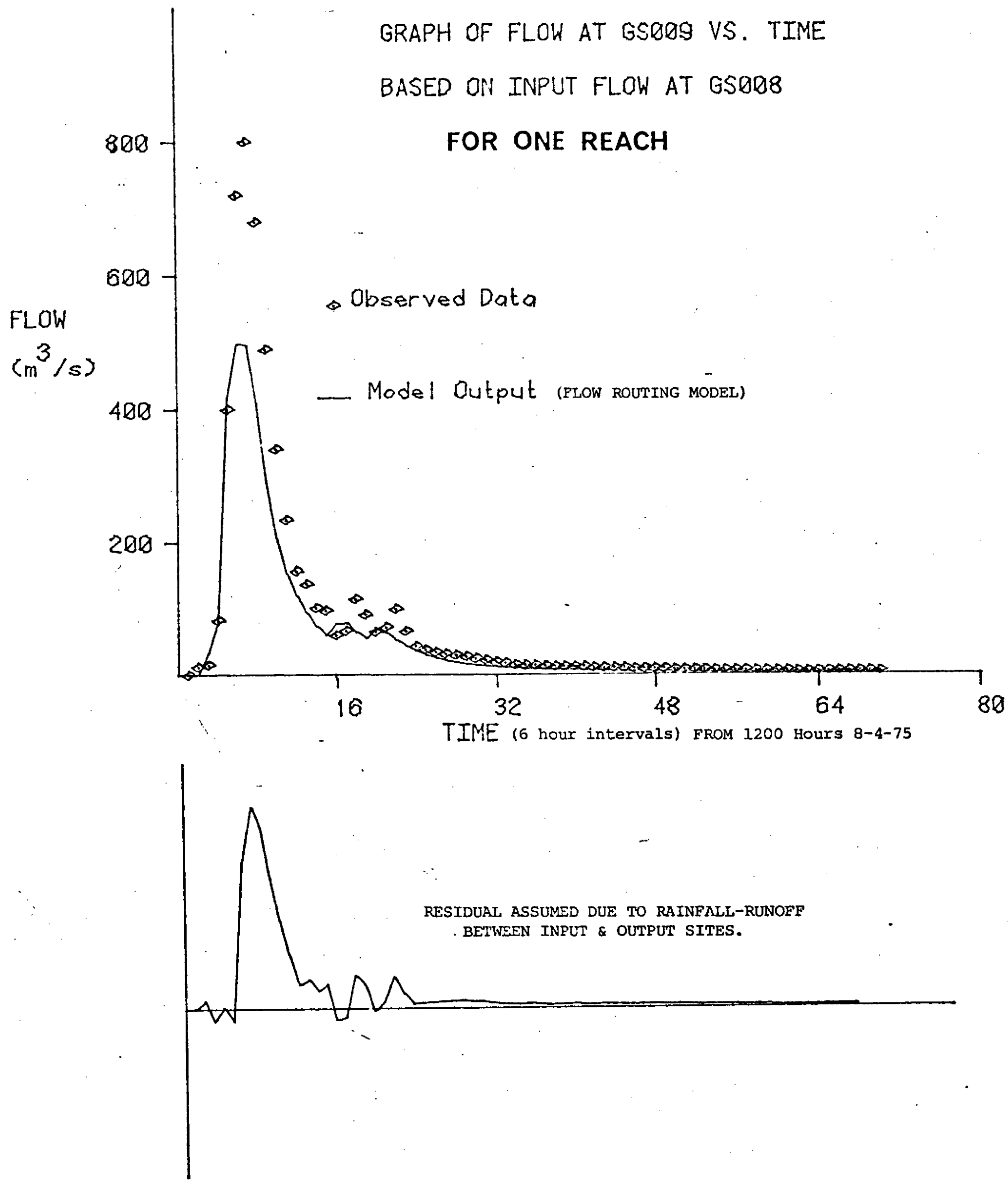

GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
FOR ONE REACH
800
600
400
200
FLOW
(m³/s)
Observed Data
Model Output (FLOW ROUTING MODEL)
16
32
48
64
80
TIME (6 hour intervals) FROM 1200 Hours 8-4-75
RESIDUAL ASSUMED DUE TO RAINFALL-RUNOFF
BETWEEN INPUT & OUTPUT SITES.

FIG. 6a

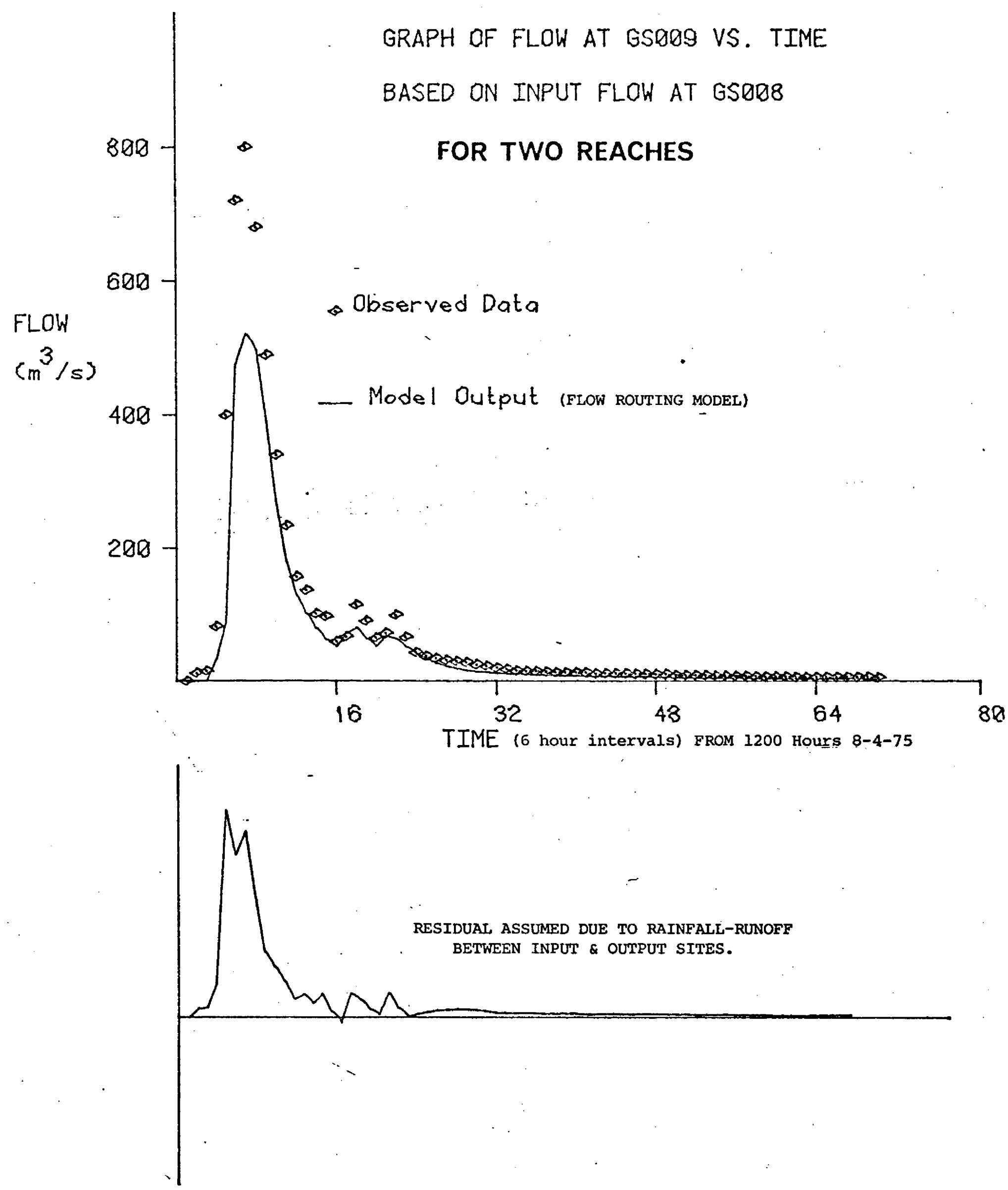

GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
FOR TWO REACHES
800
600
400
200
FLOW
(m3/s)
Observed Data
Model Output (FLOW ROUTING MODEL)
16
32
48
64
80
TIME (6 hour intervals) FROM 1200 Hours 8-4-75
RESIDUAL ASSUMED DUE TO RAINFALL-RUNOFF
BETWEEN INPUT & OUTPUT SITES.

FIG. 6b

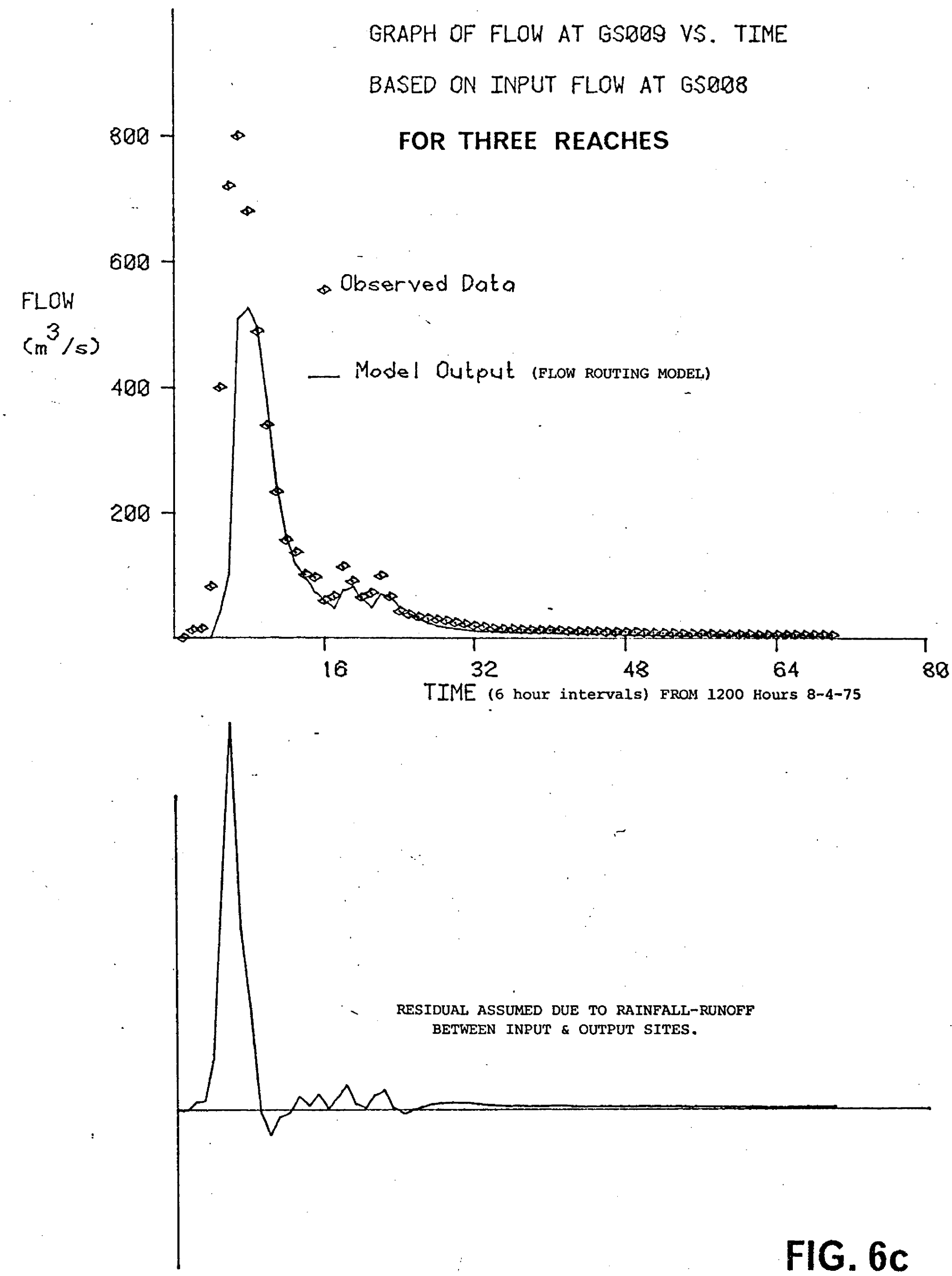
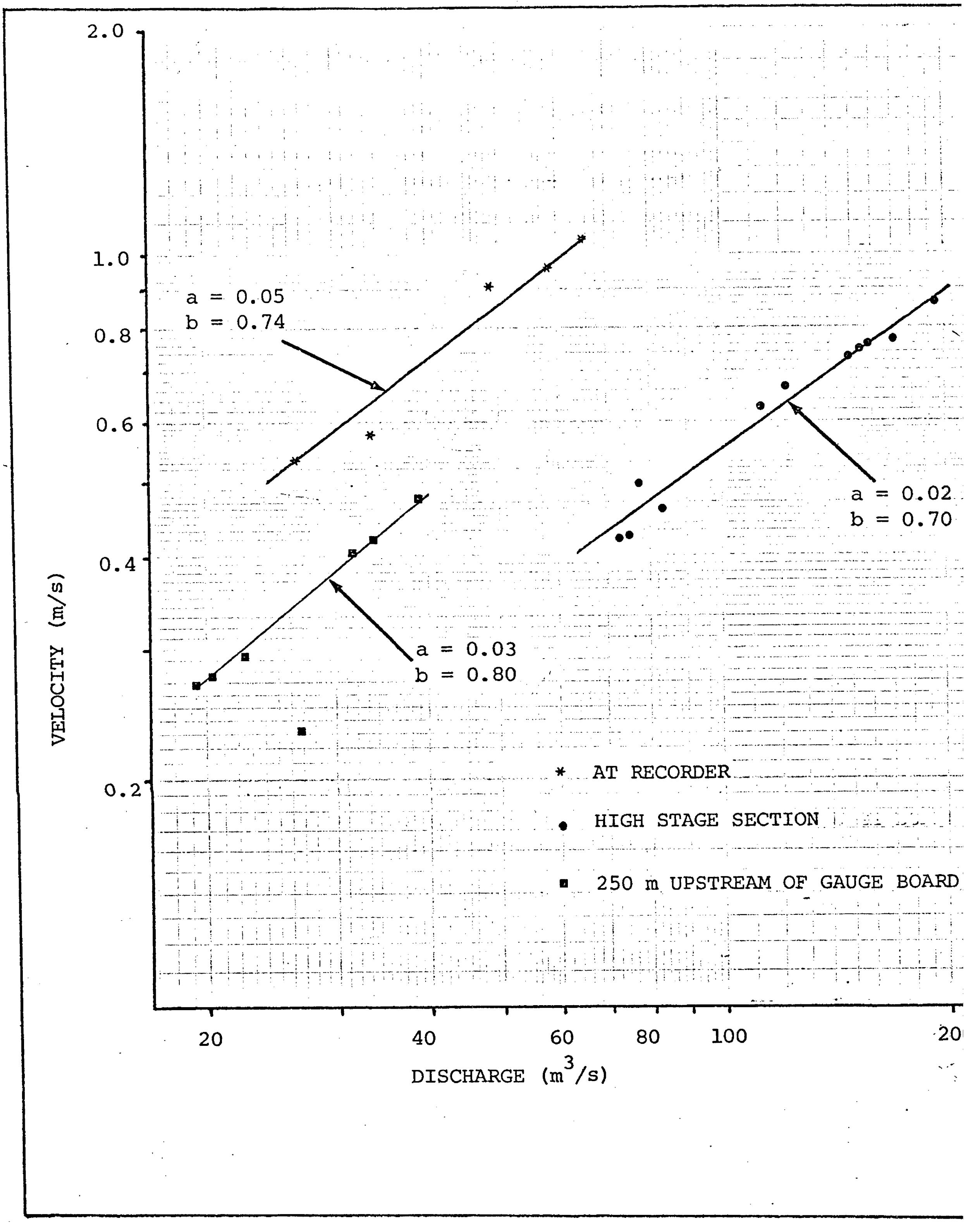

GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
FOR THREE REACHES
800
600
400
200
FLOW
(m3/s)
Observed Data
Model Output (FLOW ROUTING MODEL)
16
32
48
64
80
TIME (6 hour intervals) FROM 1200 Hours 8-4-75
RESIDUAL ASSUMED DUE TO RAINFALL-RUNOFF
BETWEEN INPUT & OUTPUT SITES.

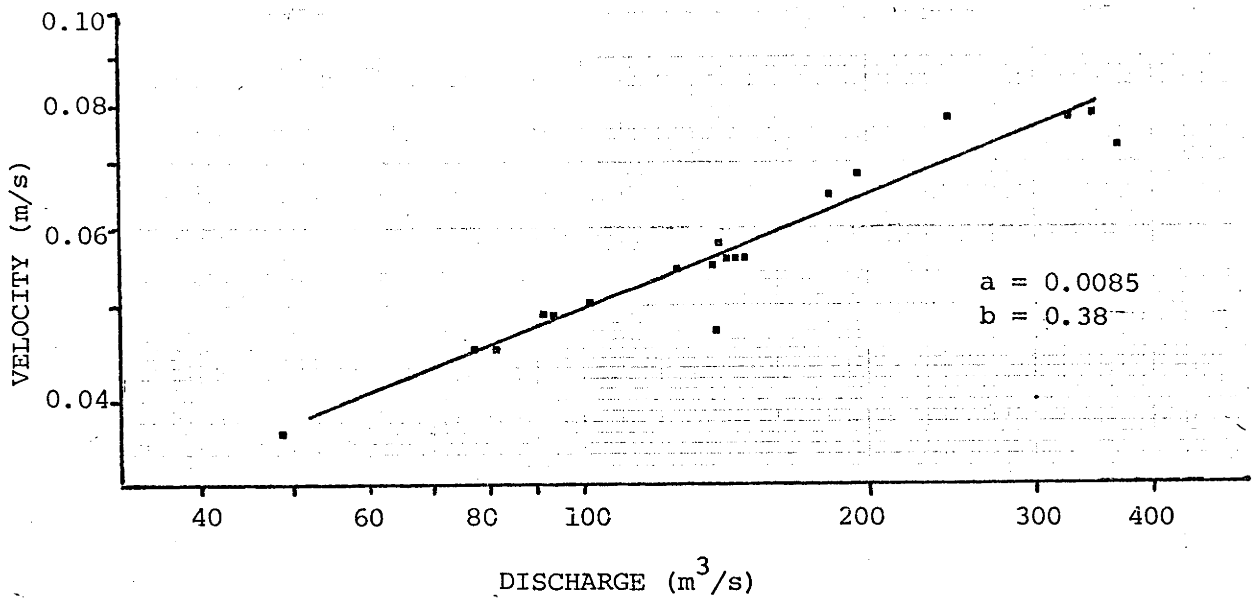
FIG. 6c



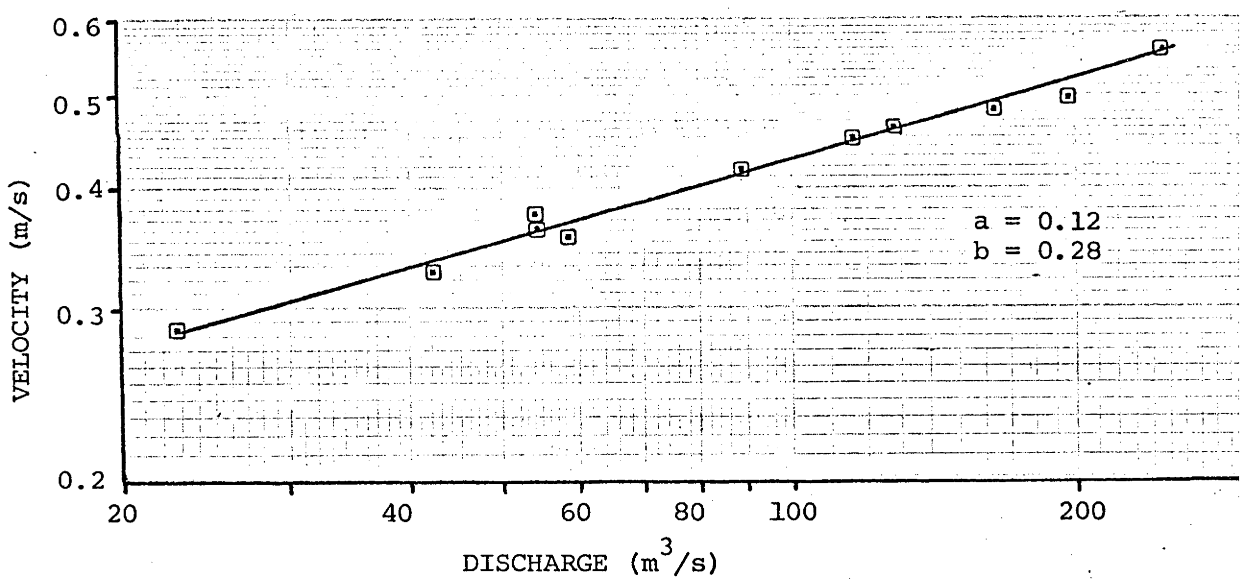
Graphs of Velocity vs. Discharge

(FOR THREE LOCATIONS IN VICINITY OF G.S.821008)

FIG. 7



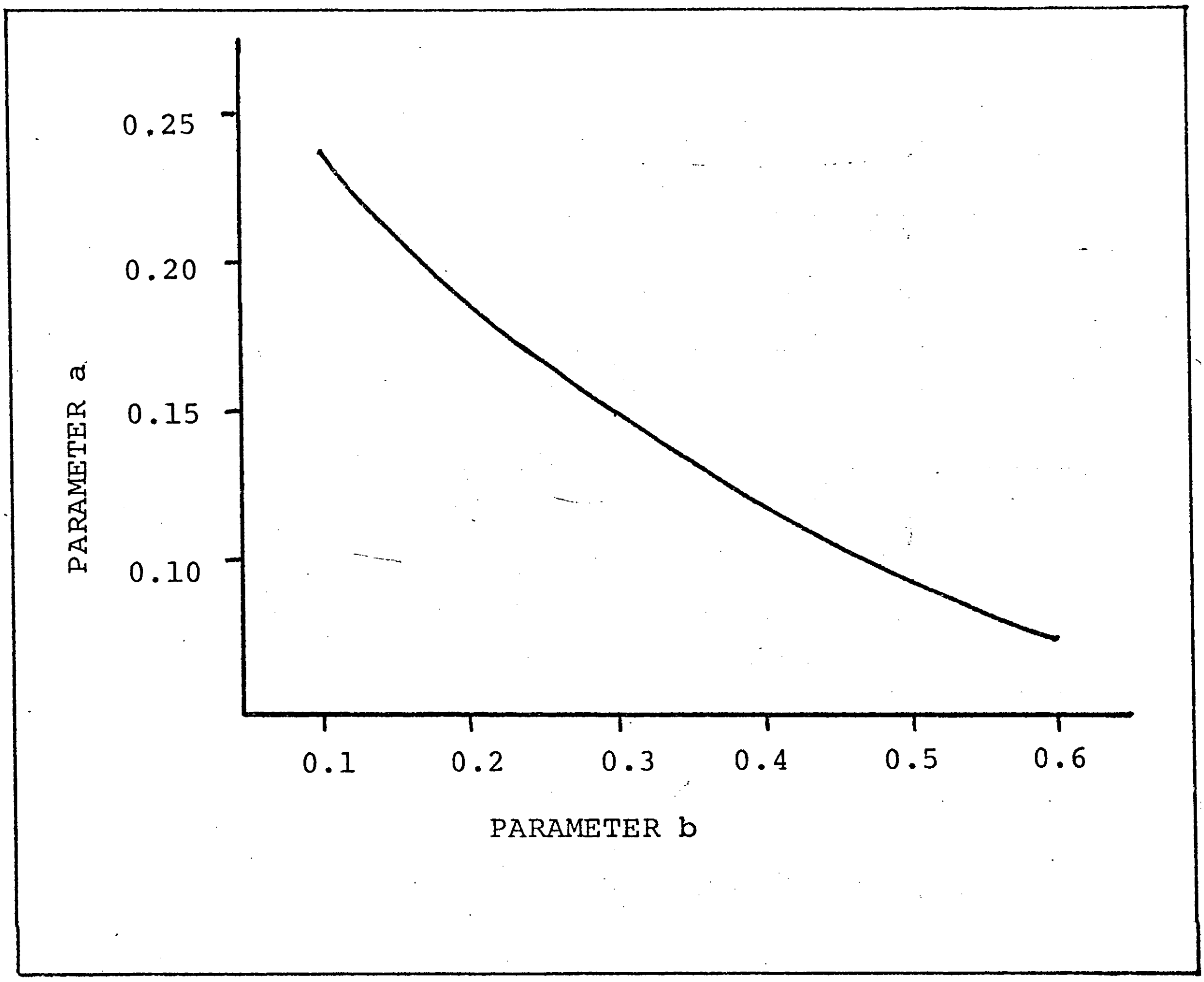
AT GAUGING STATION G.S.821019



AT GAUGING STATION G.S. 821009

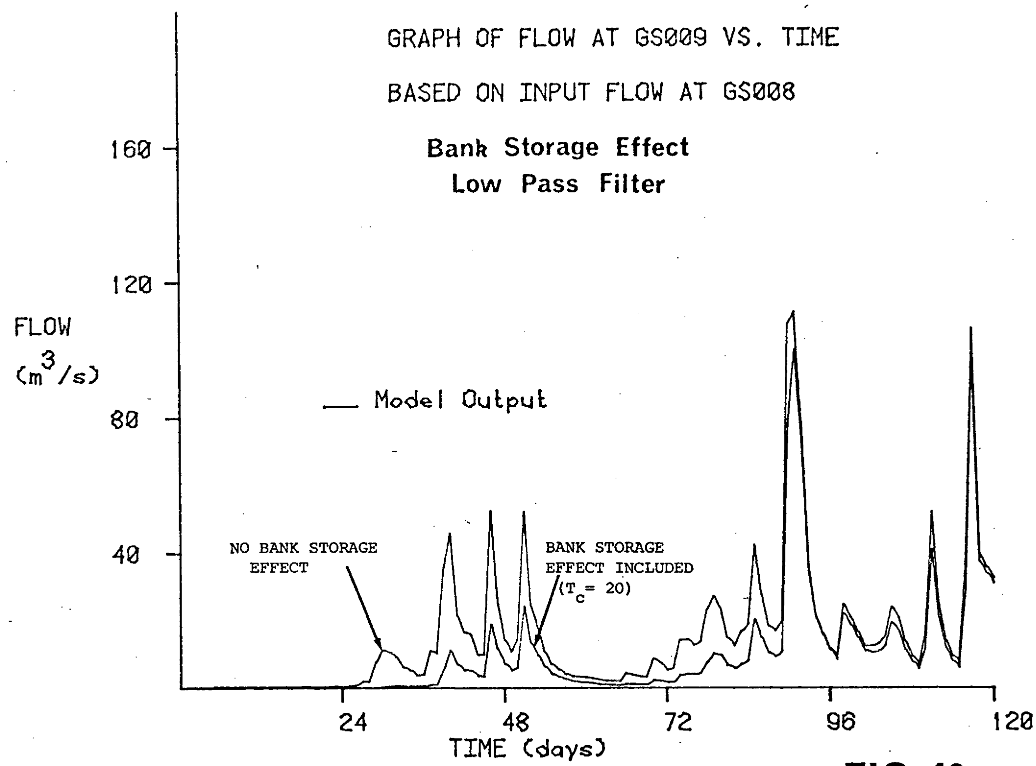
Graphs of Velocity vs. Discharge

FIG. 8



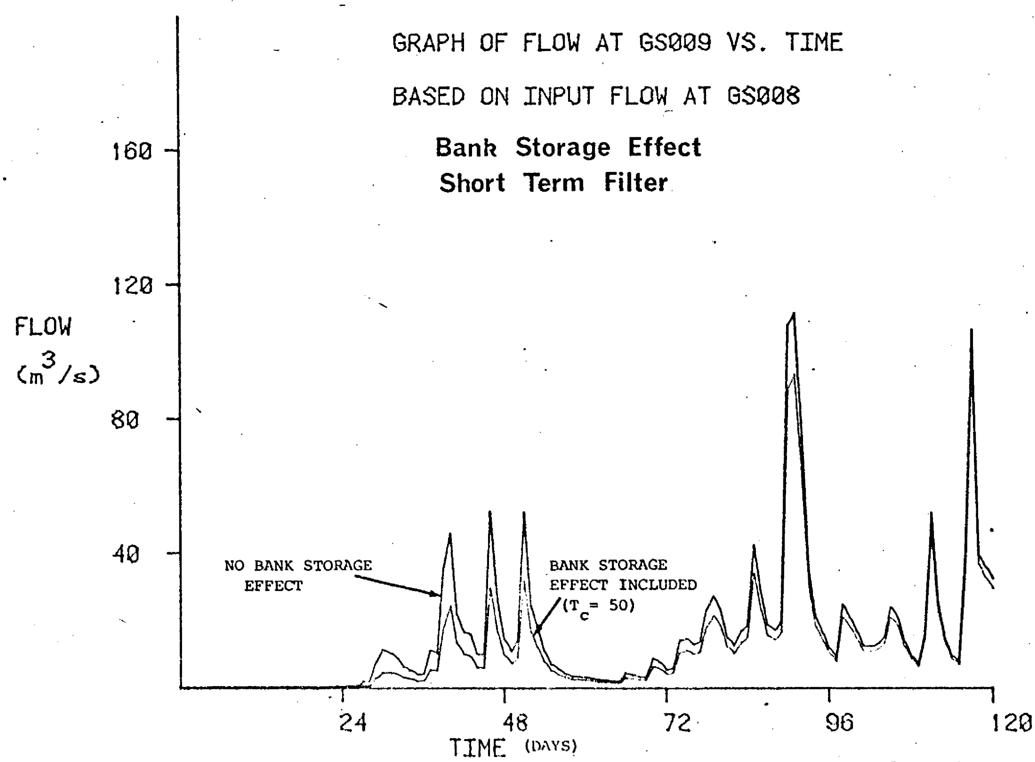
Graph of Possible a and b Parameters for Injection Point to Site 2.

FIG. 9



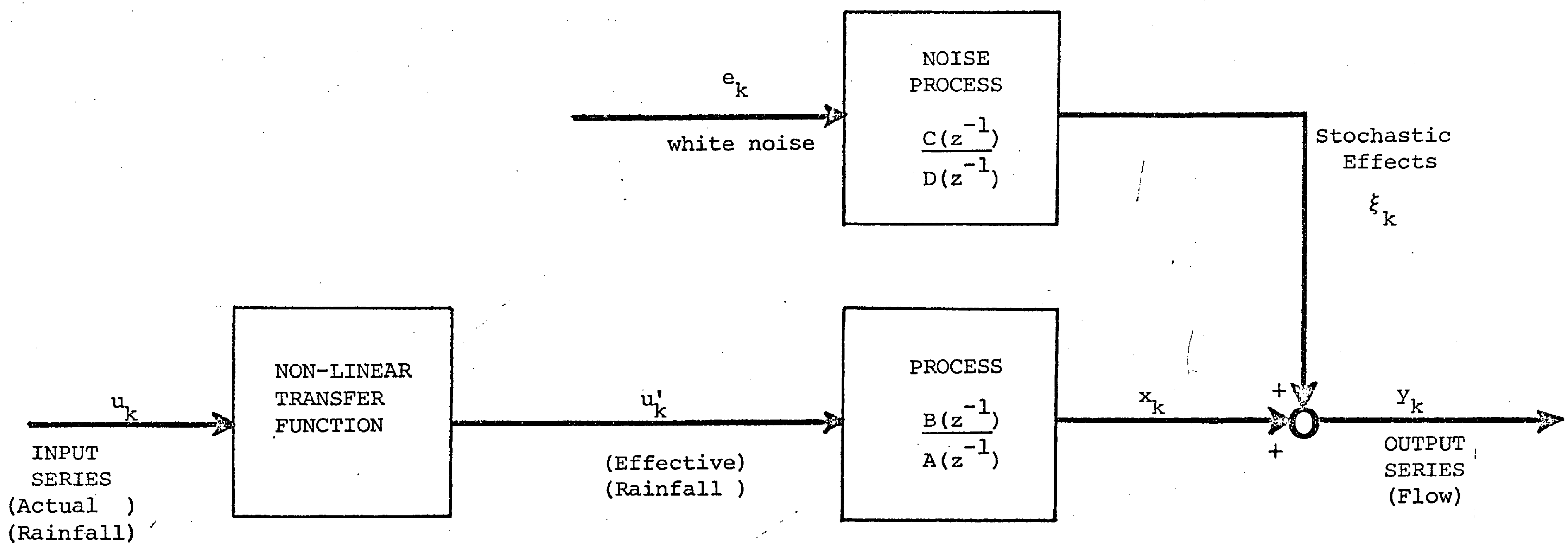
GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
Bank Storage Effect
Low Pass Filter
FLOW
(m^3/s)
160
120
80
40
— Model Output
NO BANK STORAGE EFFECT
BANK STORAGE EFFECT INCLUDED (T_c = 20)
24
48
72
96
120
TIME (days)
(FROM 1-11-77)

FIG. 10



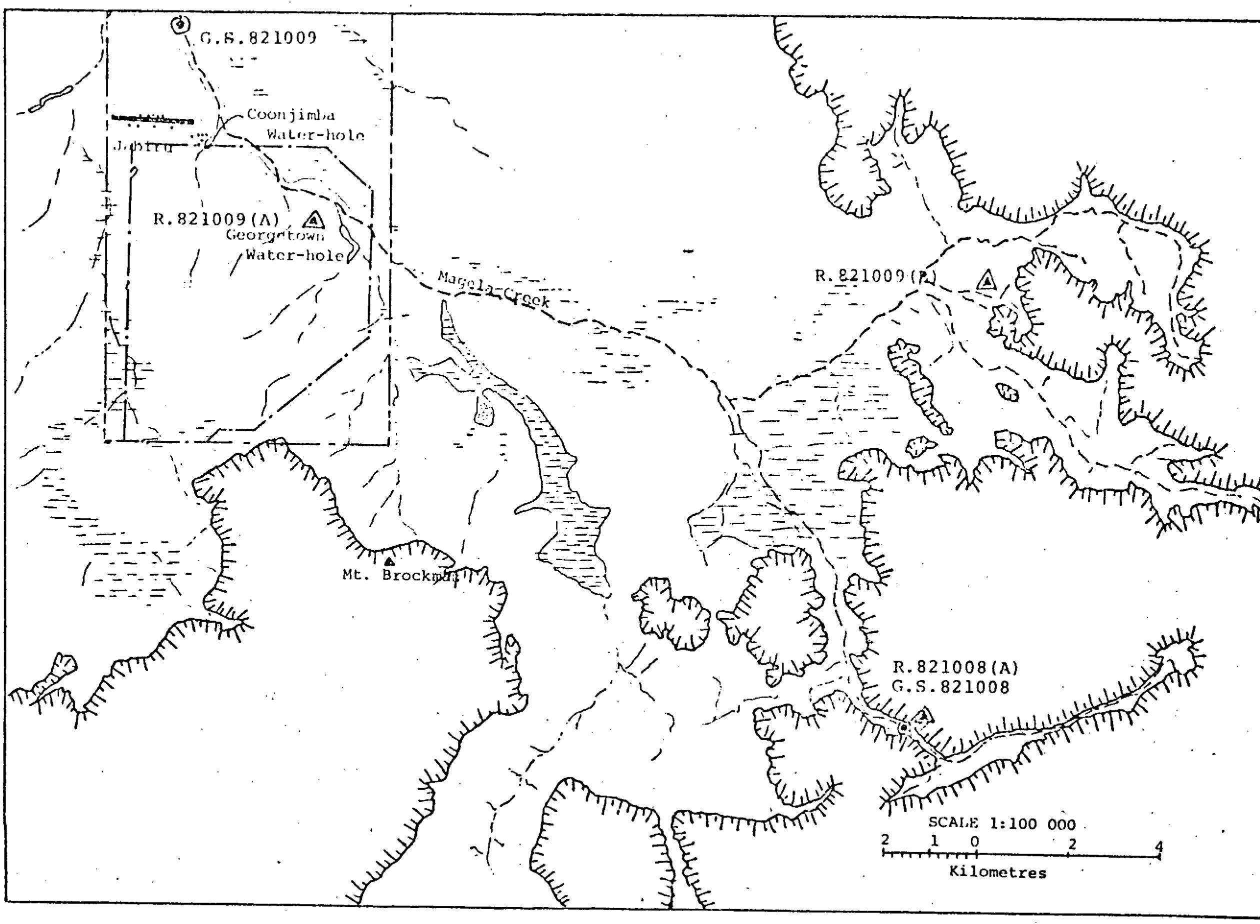
GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
Bank Storage Effect
Short Term Filter
FLOW
(m^3/s)
160
120
80
40
NO BANK STORAGE EFFECT
BANK STORAGE EFFECT INCLUDED (T_c = 50)
24
48
72
96
120
TIME (DAYS)
(FROM 1-11-77)

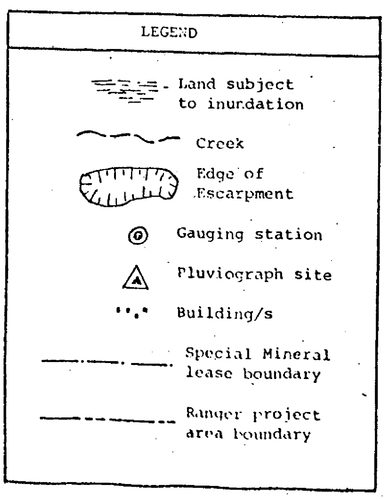
FIG. 11



RAINFALL · RUNOFF MODEL

FIG. 12





Map of Pluviograph Sites between G.S.821008 and G.S.821009

FIG. 13

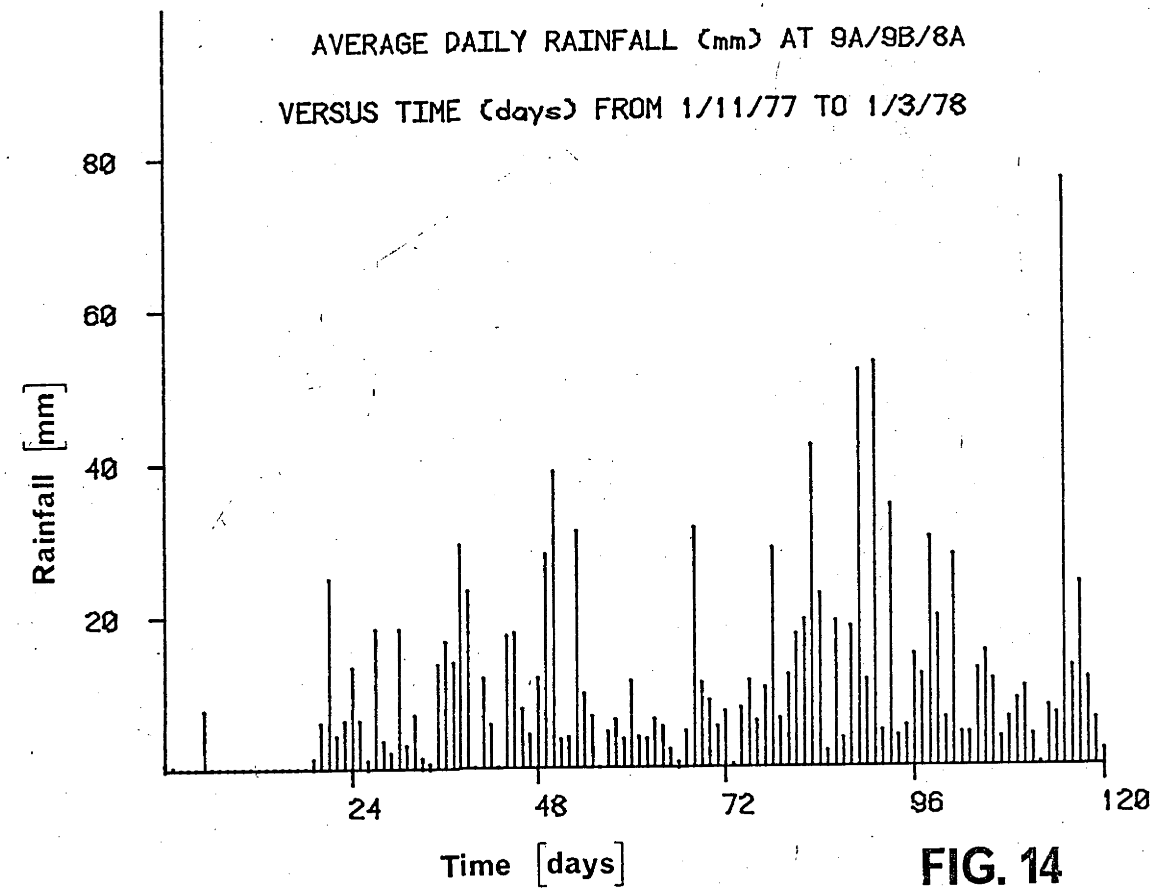

AVERAGE DAILY RAINFALL (mm) AT 9A/9B/8A
VERSUS TIME (days) FROM 1/11/77 TO 1/3/78
Rainfall [mm]
80
60
40
20
24
48
72
96
120
Time [days]

FIG. 14

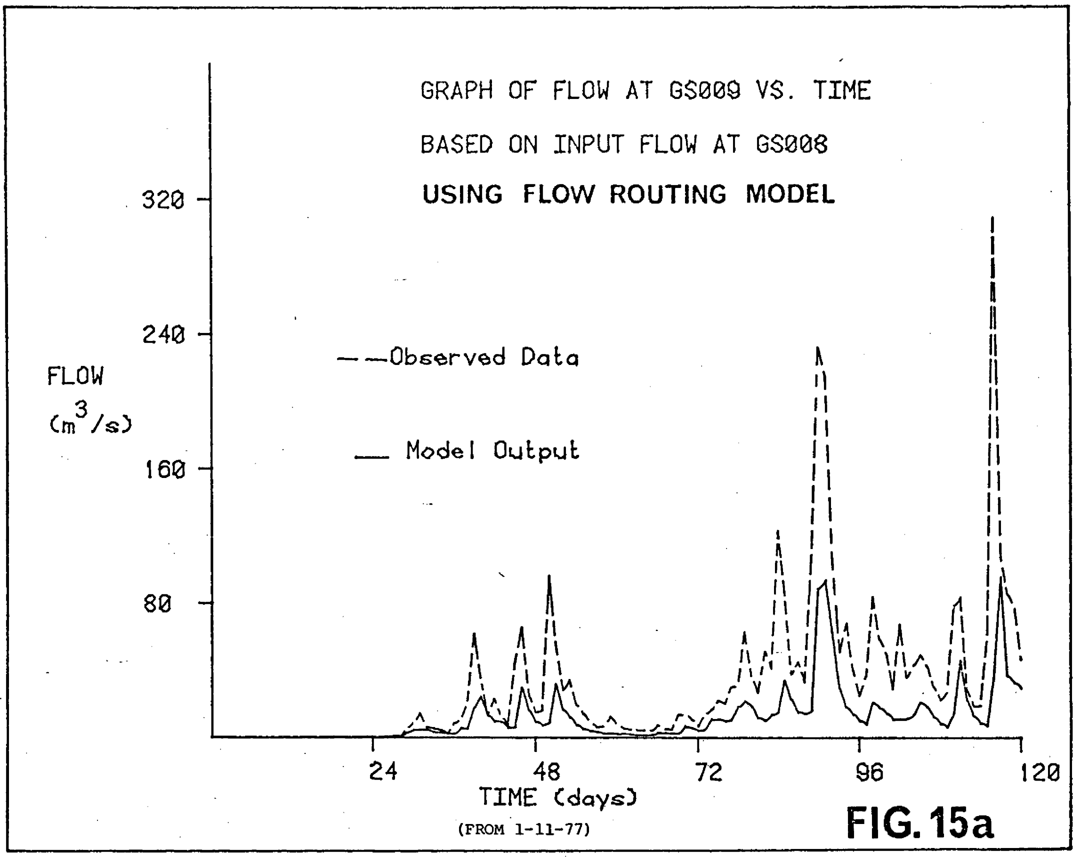


FIG. 15a

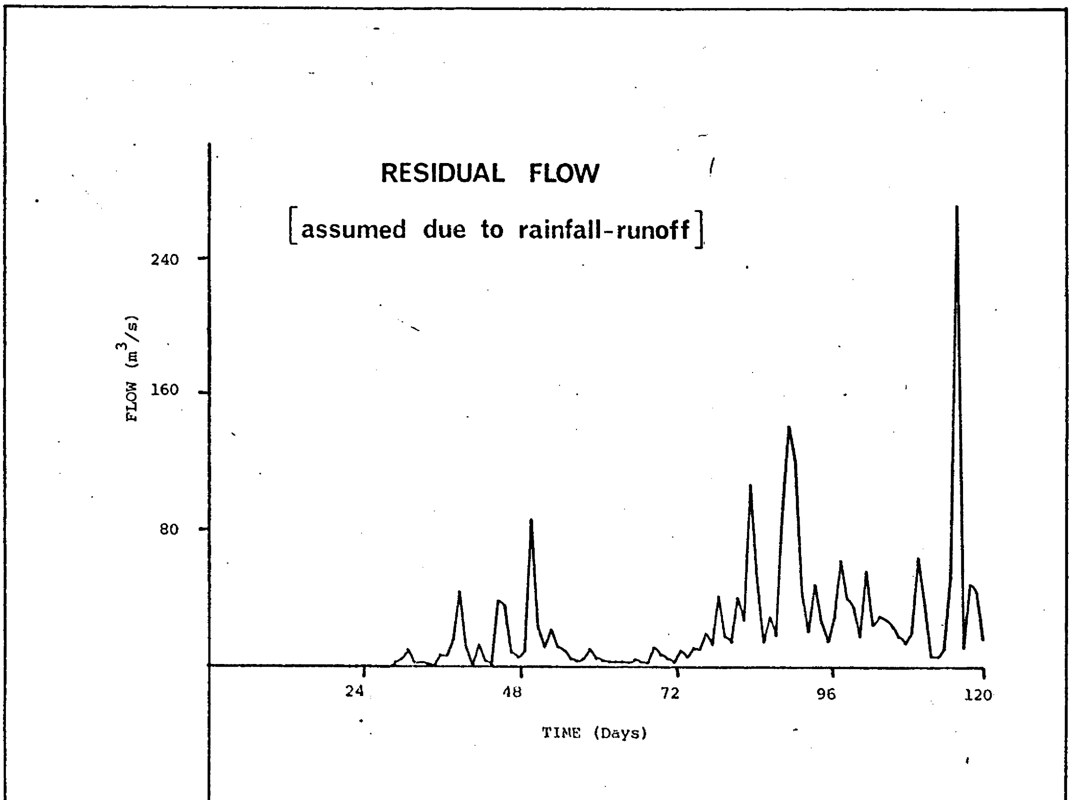


FIG. 15b

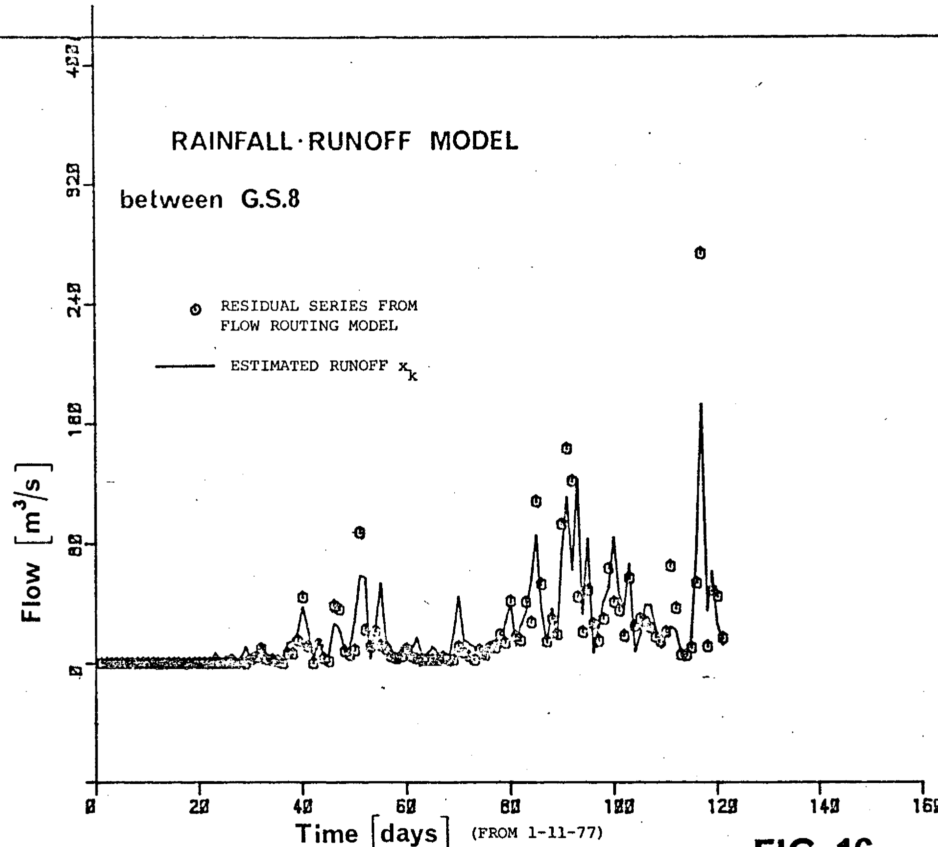

RAINFALL·RUNOFF MODEL
between G.S.8
RESIDUAL SERIES FROM FLOW ROUTING MODEL
ESTIMATED RUNOFF x_k
Flow $[m^3/s]$
Time [days] (FROM 1-11-77)

FIG. 16

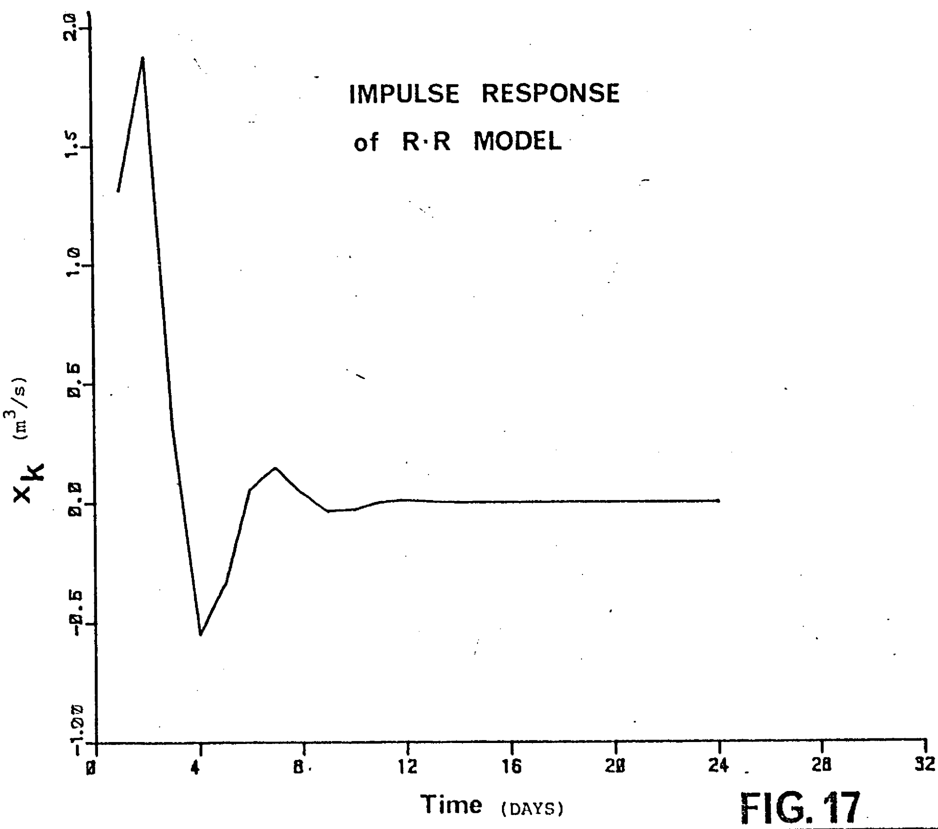

IMPULSE RESPONSE
of R·R MODEL
x_k (m^3/s)
Time (DAYS)

FIG. 17

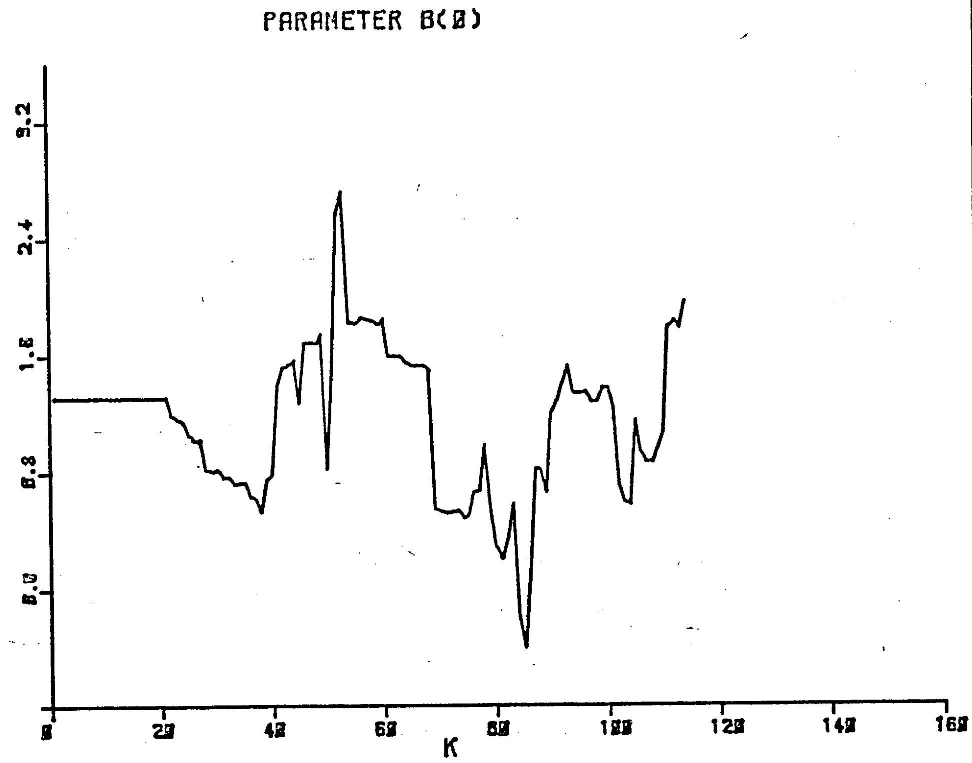


FIG. 18a

RECURSIVE ESTIMATES of b PARAMETERS

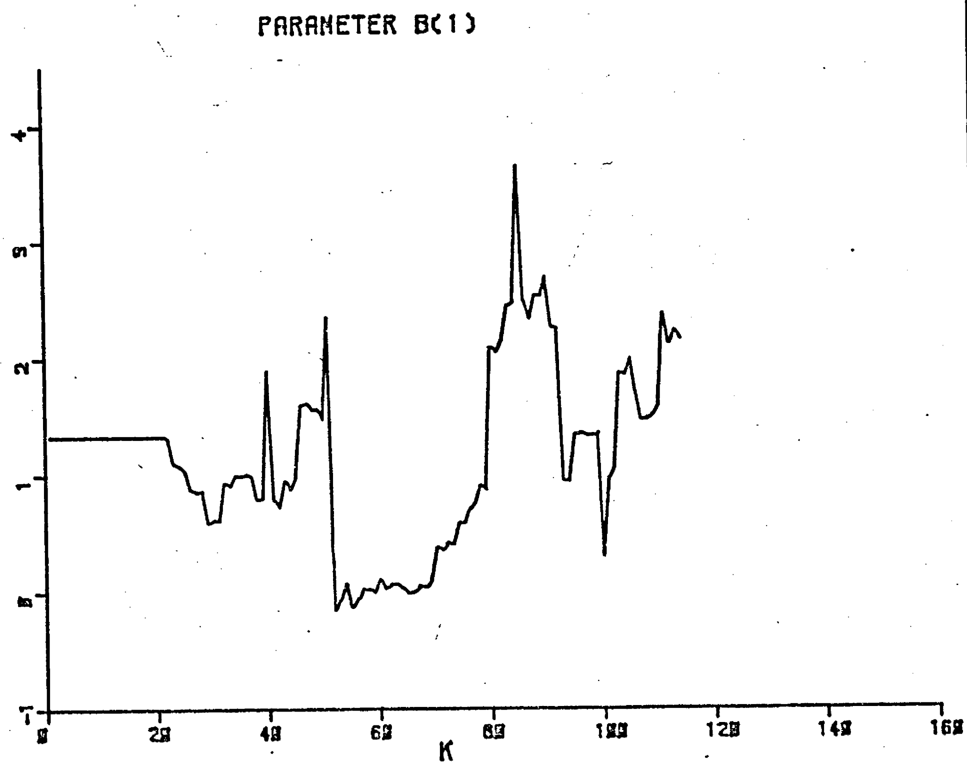


FIG. 18b

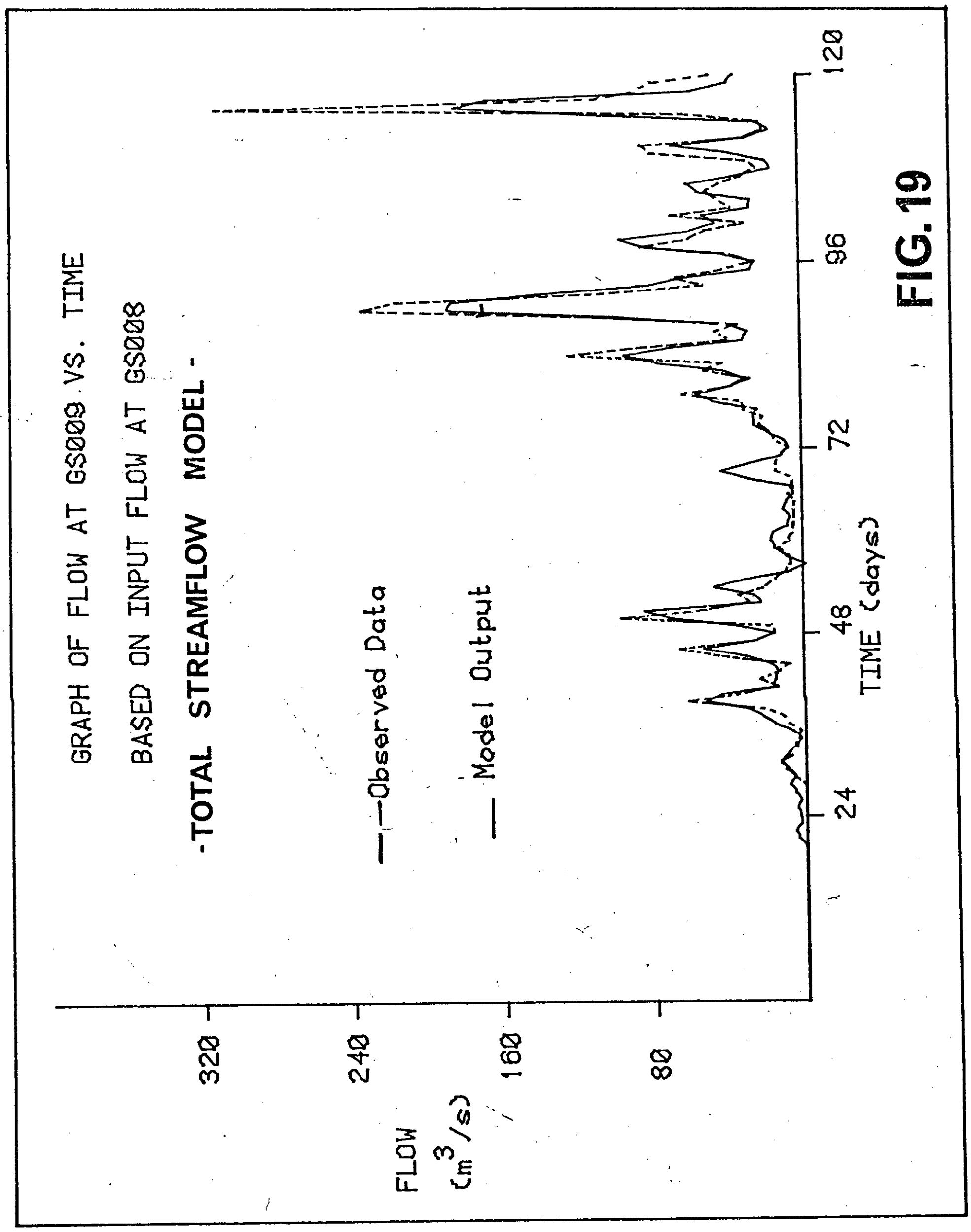

GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
-TOTAL STREAMFLOW MODEL -
Observed Data
Model Output
FLOW
(m3/s)
320
240
160
80
24
48
72
96
120
TIME (days)

FIG. 19

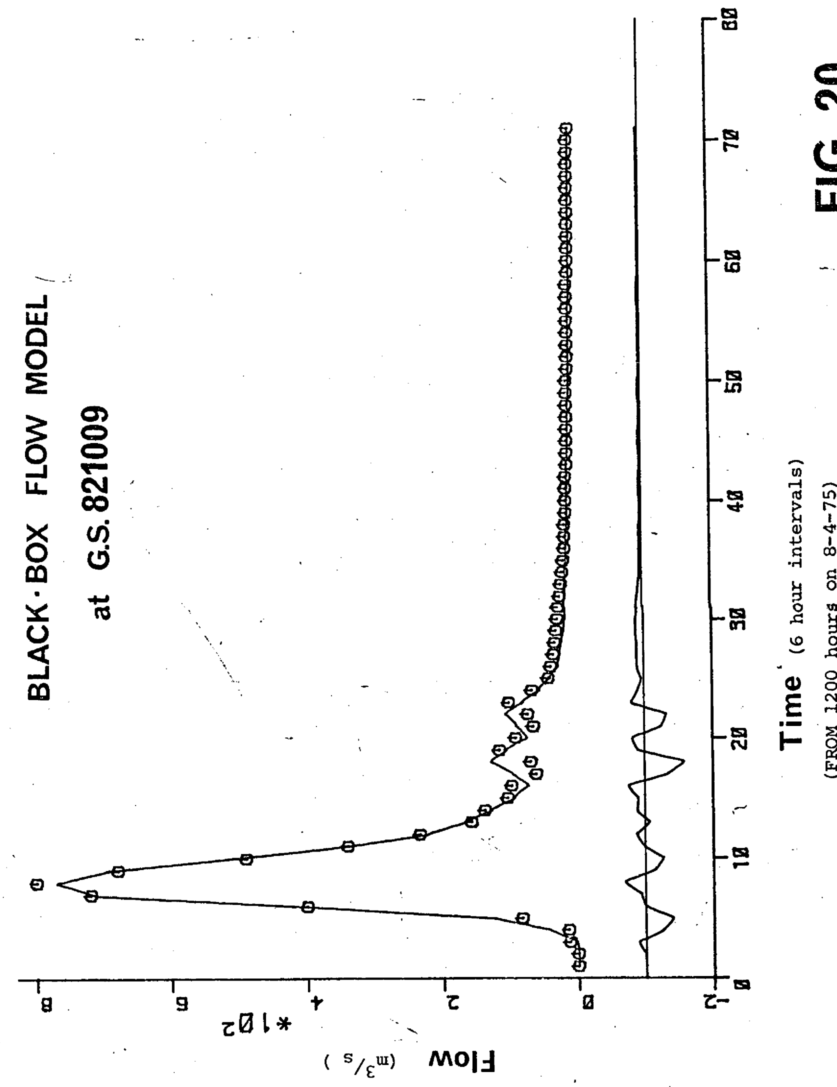
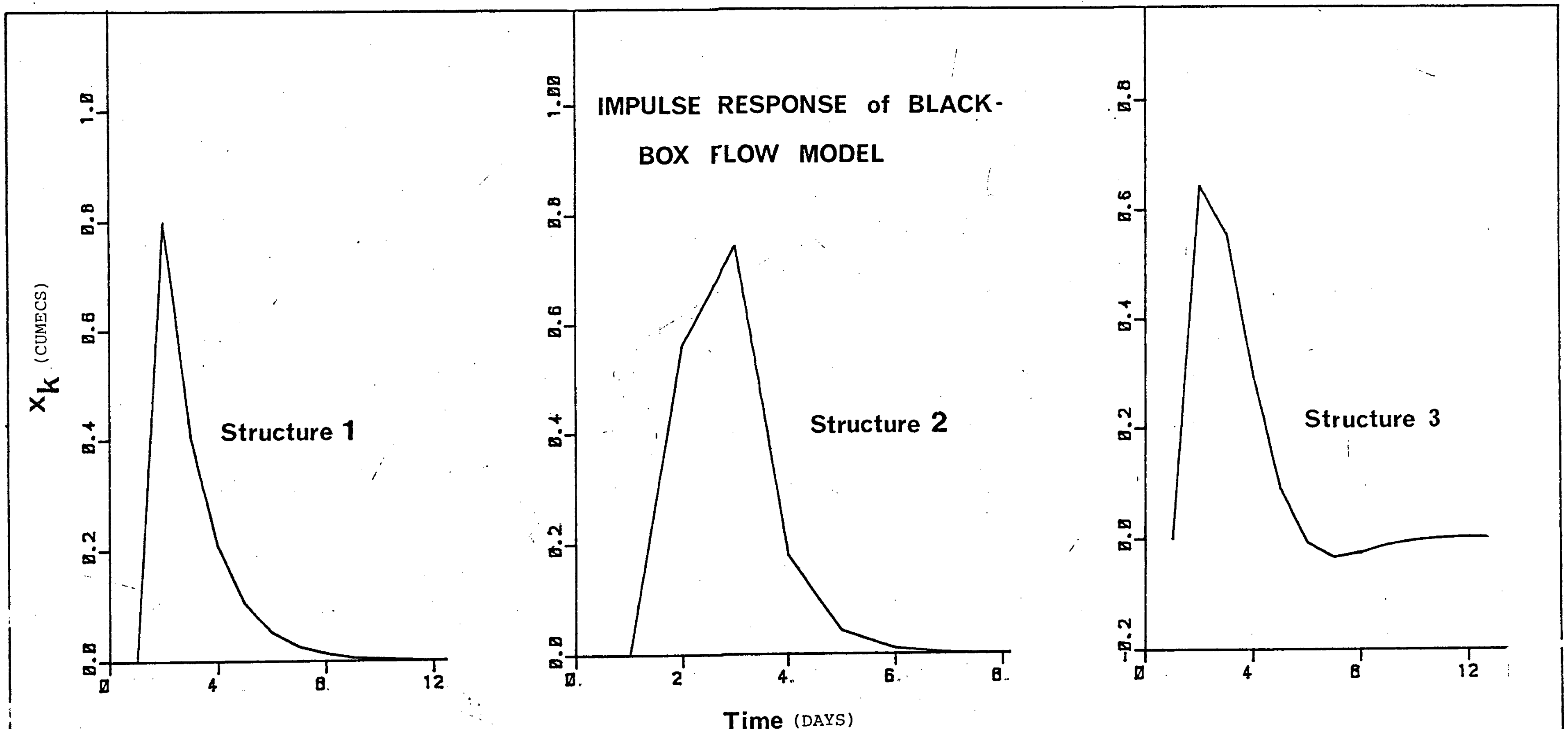
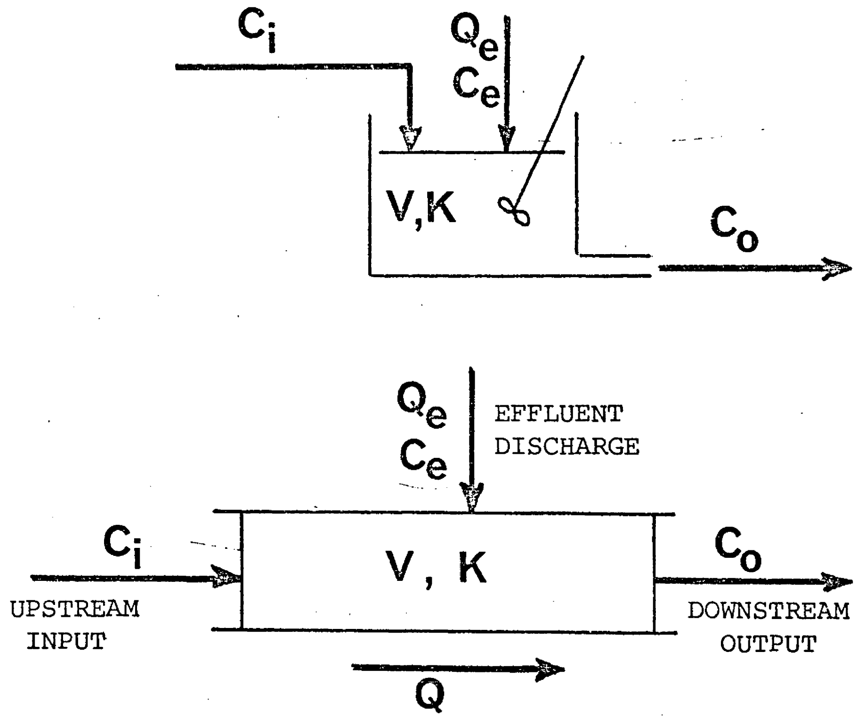

BLACK·BOX FLOW MODEL
at G.S. 821009
Flow (m³/s)
*10²
Time (6 hour intervals)
(FROM 1200 hours on 8-4-75)

FIG. 20



IMPULSE RESPONSE of BLACK-BOX FLOW MODEL
x_k (CUMECS)
Structure 1
Structure 2
Structure 3
Time (DAYS)

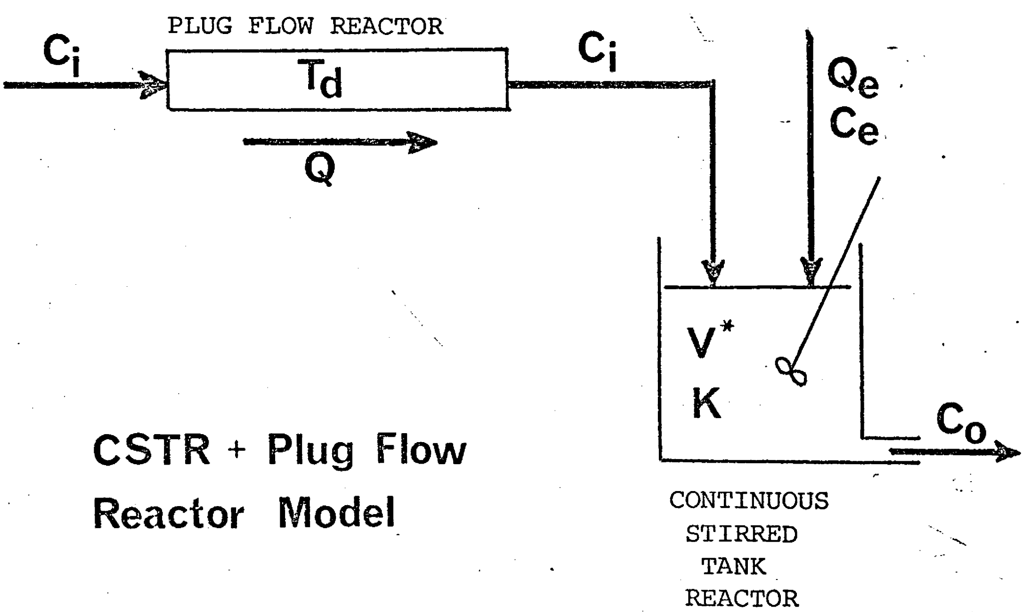
FIG. 21



CSTR Model

SINGLE REACH OF RIVER

FIG. 22a



CSTR + Plug Flow Reactor Model

(ALL VARIABLES ARE AS DEFINED FOR EQUATION)

FIG. 22b

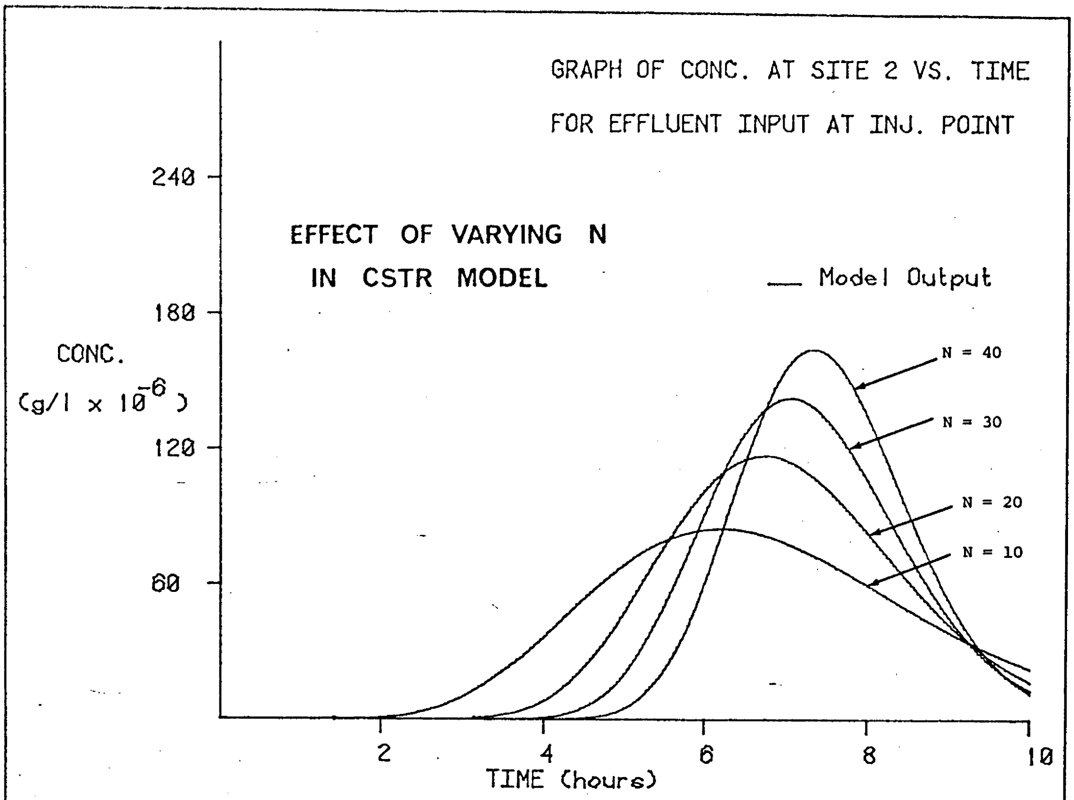

GRAPH OF CONC. AT SITE 2 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
EFFECT OF VARYING N
IN CSTR MODEL
Model Output
N = 40
N = 30
N = 20
N = 10
240
180
120
60
CONC.
(g/l x 10^{-6})
2
4
6
8
10
TIME (hours)
(MEASURED FROM TIME OF EFFLUENT IMPULSE)

FIG. 23

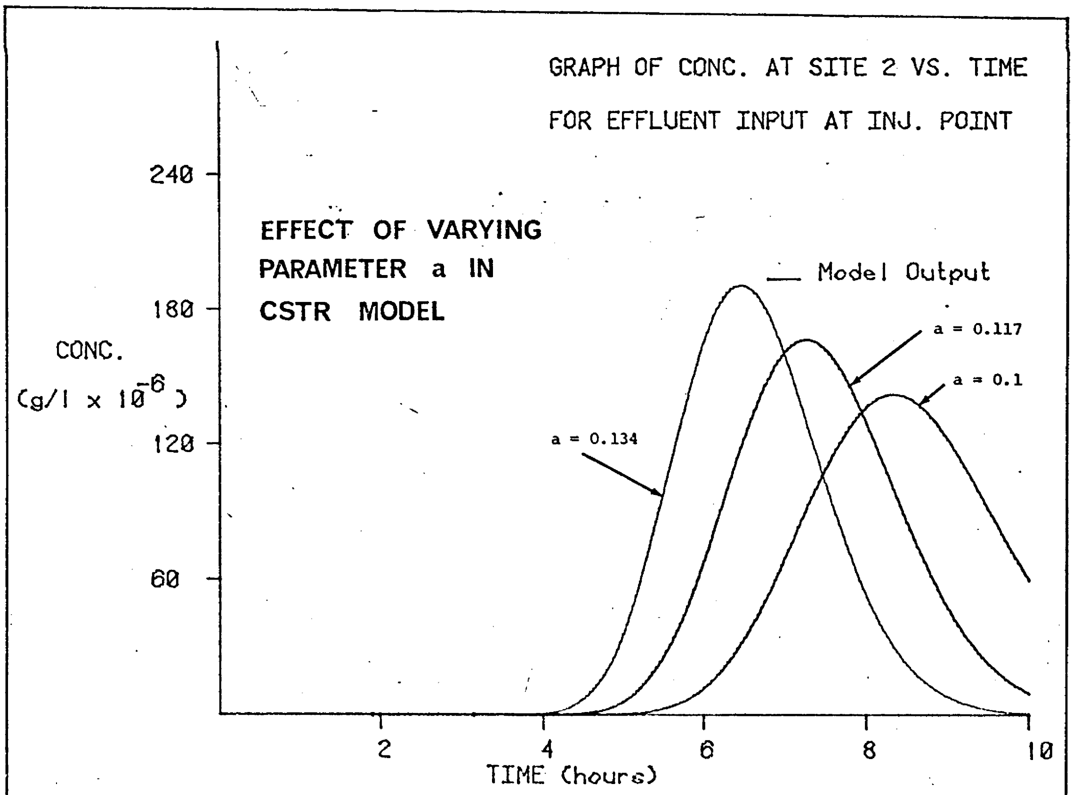

GRAPH OF CONC. AT SITE 2 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
EFFECT OF VARYING
PARAMETER a IN
CSTR MODEL
Model Output
a = 0.117
a = 0.1
a = 0.134
240
180
120
60
CONC.
(g/l x 10^{-6})
2
4
6
8
10
TIME (hours)
(MEASURED FROM TIME OF EFFLUENT IMPULSE)

FIG. 24

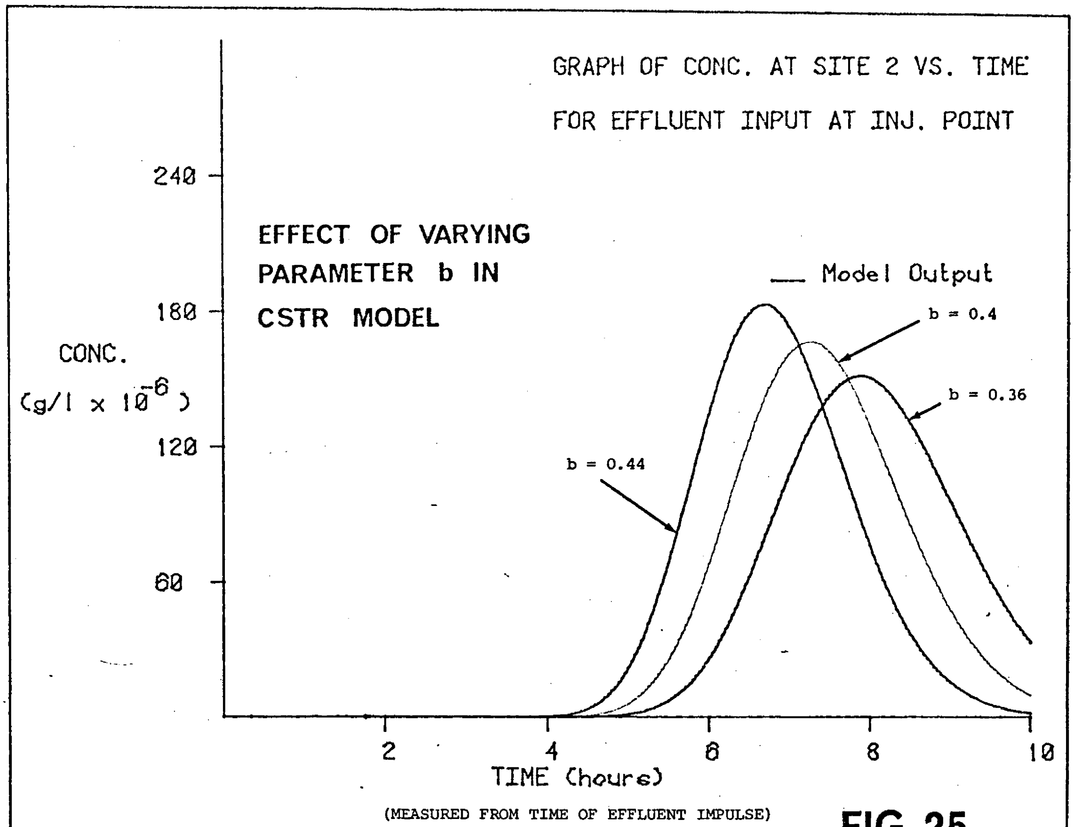

GRAPH OF CONC. AT SITE 2 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
EFFECT OF VARYING PARAMETER b IN CSTR MODEL
Model Output
b = 0.4
b = 0.36
b = 0.44
CONC. (g/l x 10^-6)
240
180
120
60
2
4
6
8
10
TIME (hours)
(MEASURED FROM TIME OF EFFLUENT IMPULSE)

FIG. 25

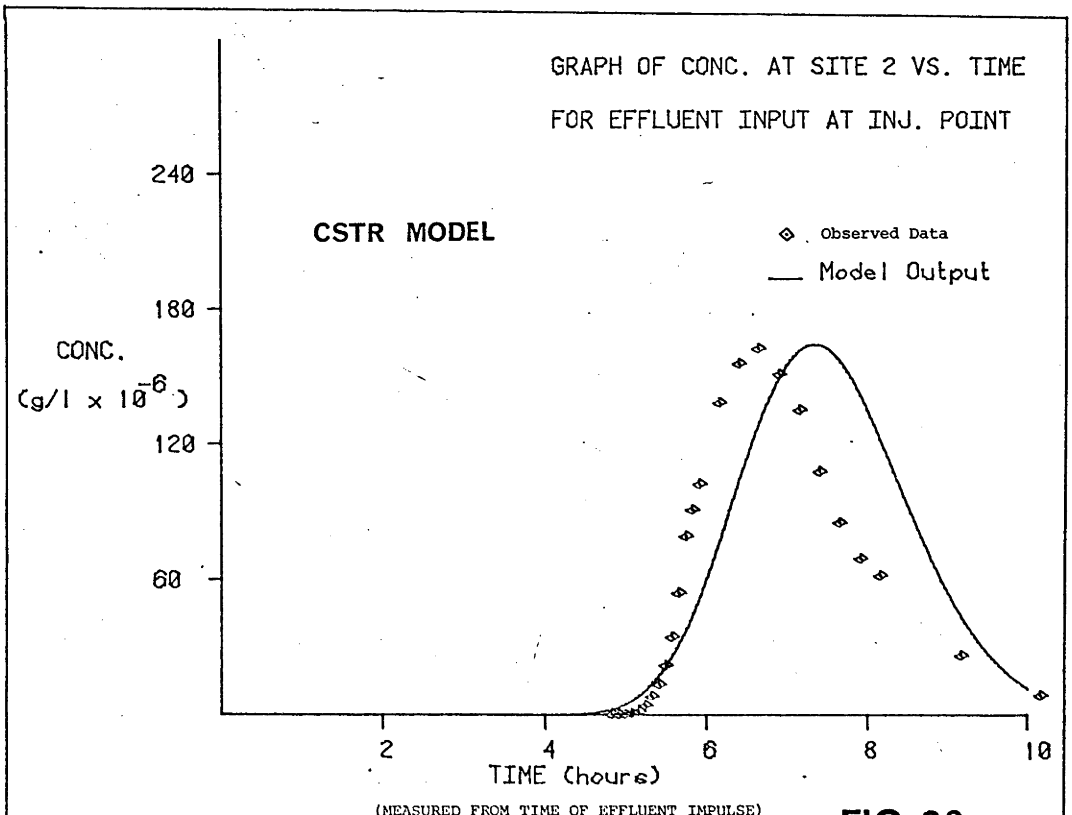

GRAPH OF CONC. AT SITE 2 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
CSTR MODEL
Observed Data
Model Output
CONC. (g/l x 10^-6)
240
180
120
60
2
4
6
8
10
TIME (hours)
(MEASURED FROM TIME OF EFFLUENT IMPULSE)

FIG. 26

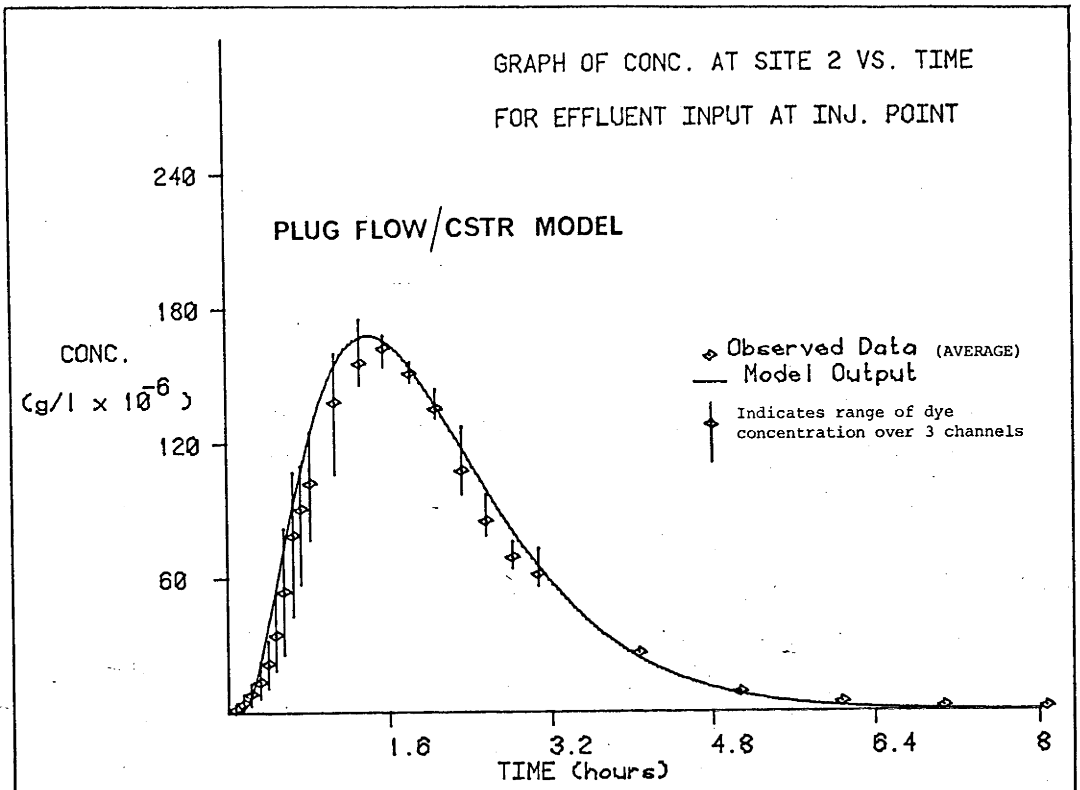

GRAPH OF CONC. AT SITE 2 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
PLUG FLOW/CSTR MODEL
240
180
120
60
CONC.
(g/l x 10^-6)
Observed Data (AVERAGE)
Model Output
Indicates range of dye concentration over 3 channels
1.6
3.2
4.8
6.4
8
TIME (hours)
(FOR TIME AFTER EFFLUENT IMPULSE ADD PURE TIME DELAY OF 5.1 HOURS)

FIG. 27

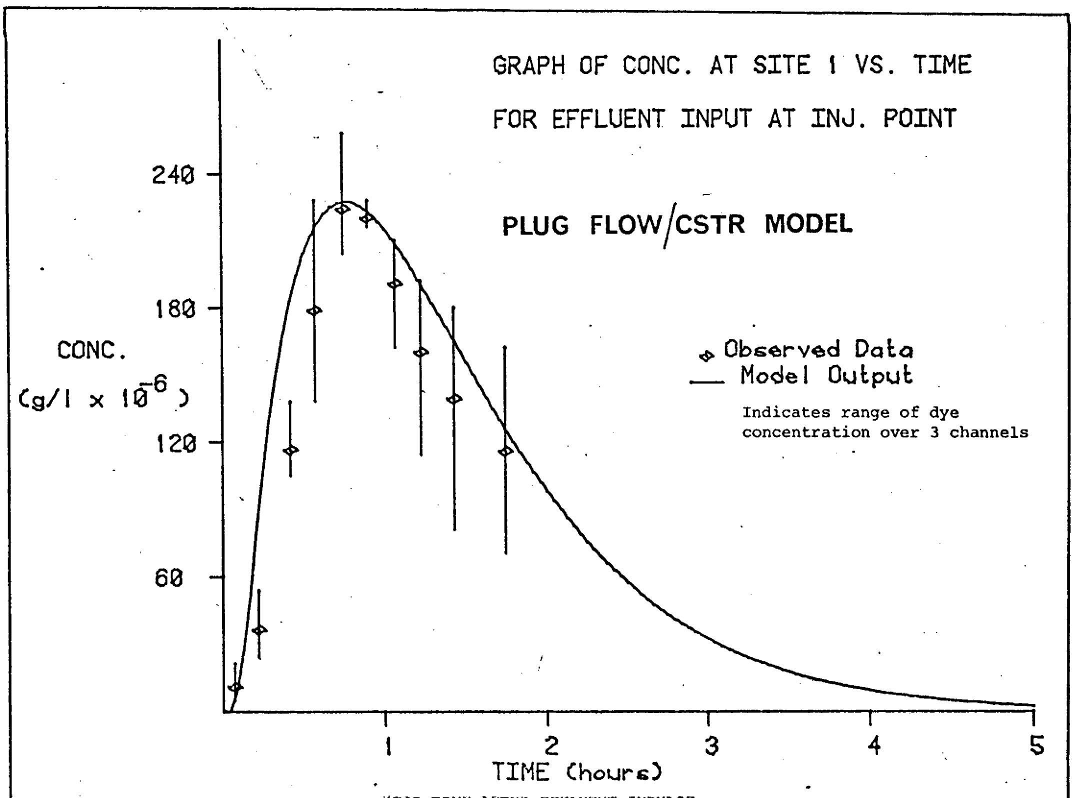
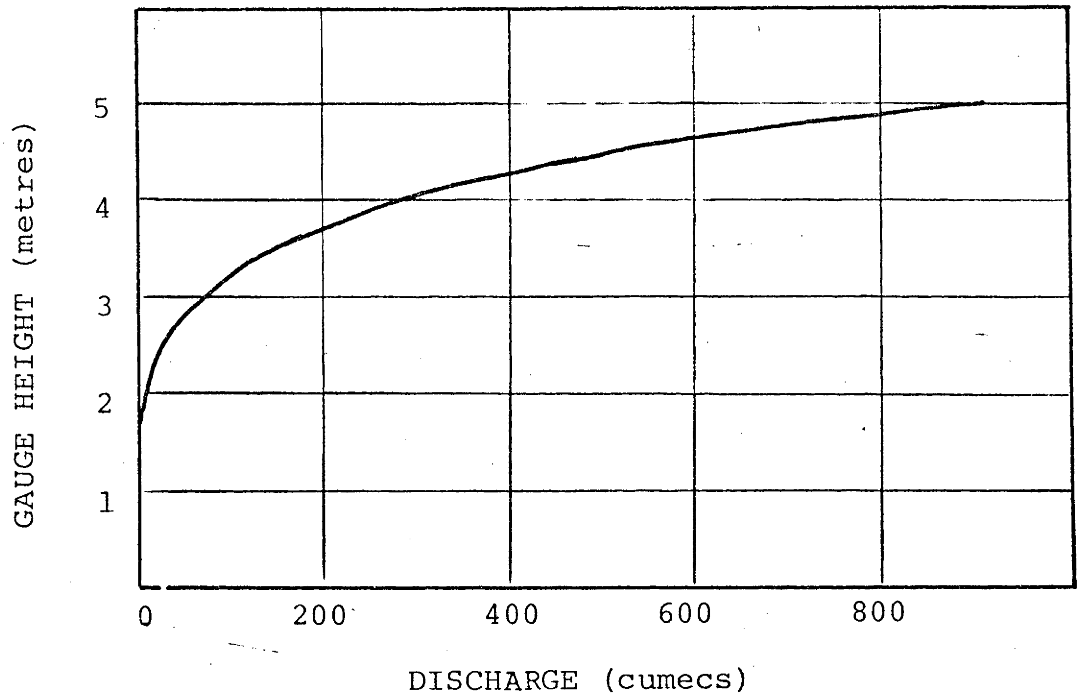
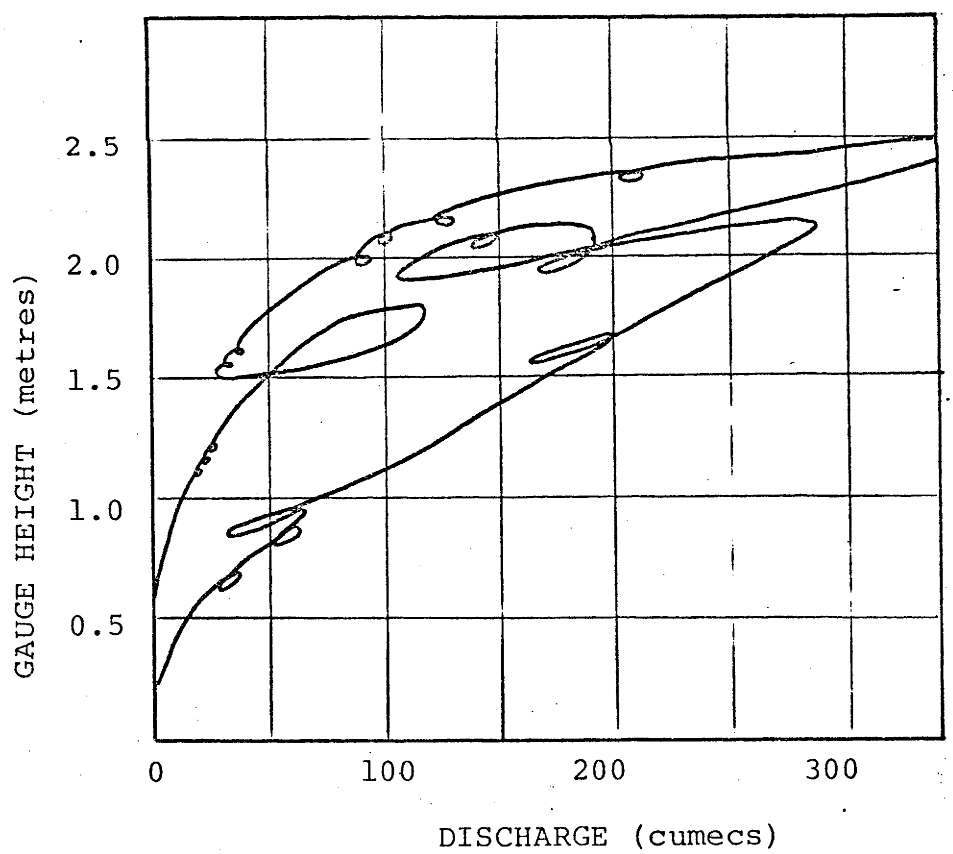

GRAPH OF CONC. AT SITE 1 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
PLUG FLOW/CSTR MODEL
240
180
120
60
CONC.
(g/l x 10^-6)
Observed Data
Model Output
Indicates range of dye concentration over 3 channels
1
2
3
4
5
TIME (hours)
(FOR TIME AFTER EFFLUENT IMPULSE ADD PURE TIME DELAY OF 3.1 HOURS)

FIG. 28



MAGELA CREEK G.S.821009

RATING CURVE



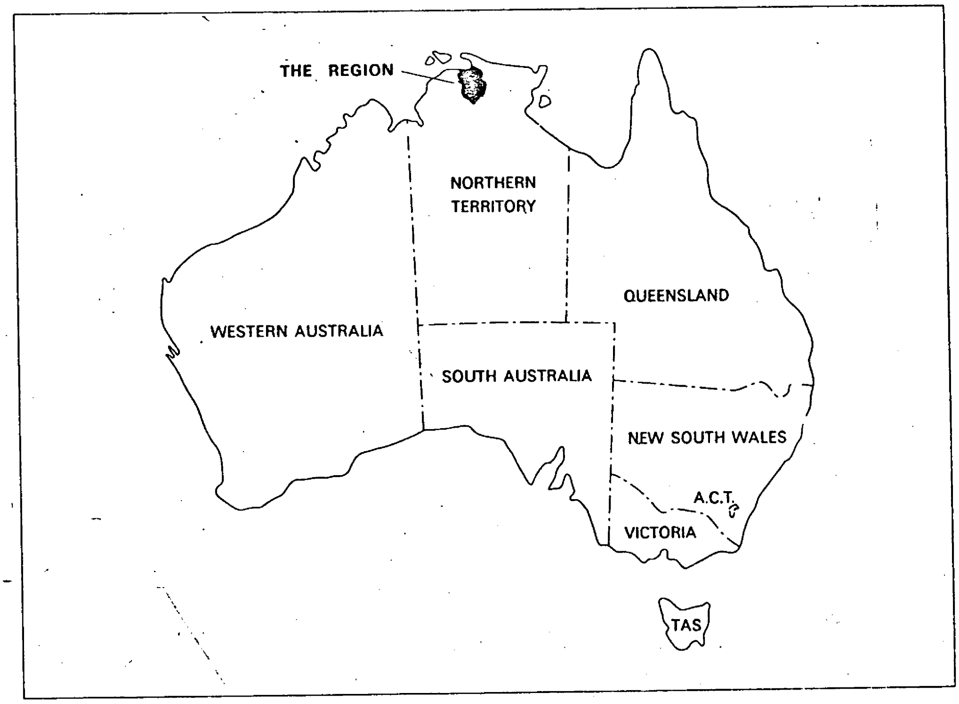
MAGELA CREEK G.S.821017

LOOP RATING CURVE

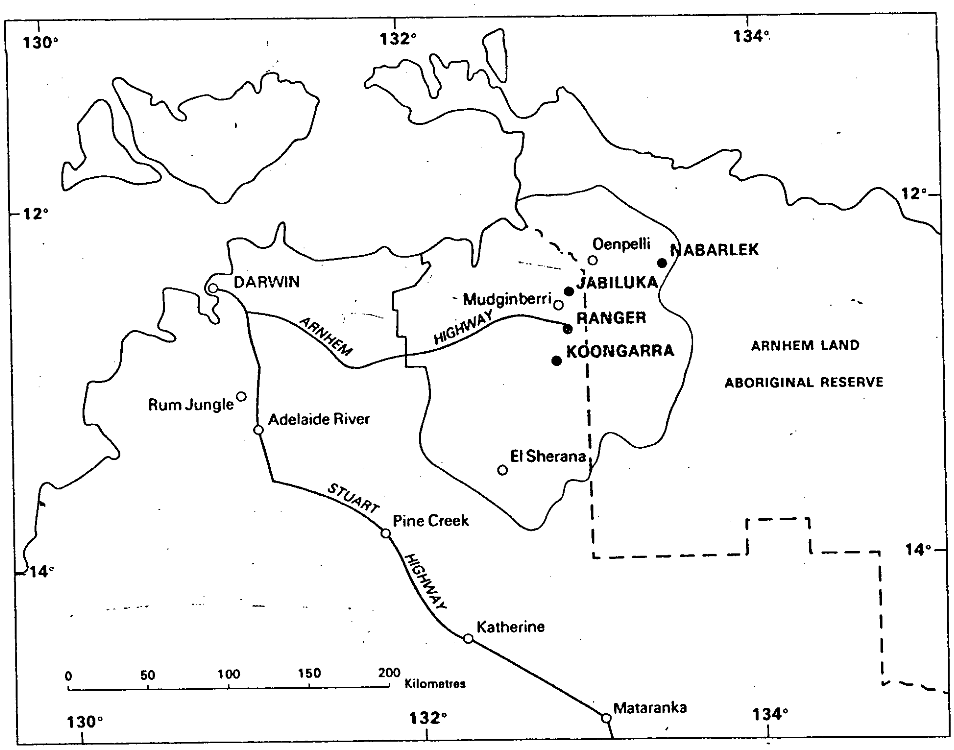
{ FROM: N.T. Dept. of Transport & Works
'Uranium Province Hydrology 1978 }

FIG. 29

ALLIGATOR RIVERS REGION & MINE SITES



Location Maps



(from: Ranger Uranium Environ. Inquiry, 2nd Rep.)

FIG. 1

(from; Ranger Uran. Environ. Inquiry, 2nd Rep.)

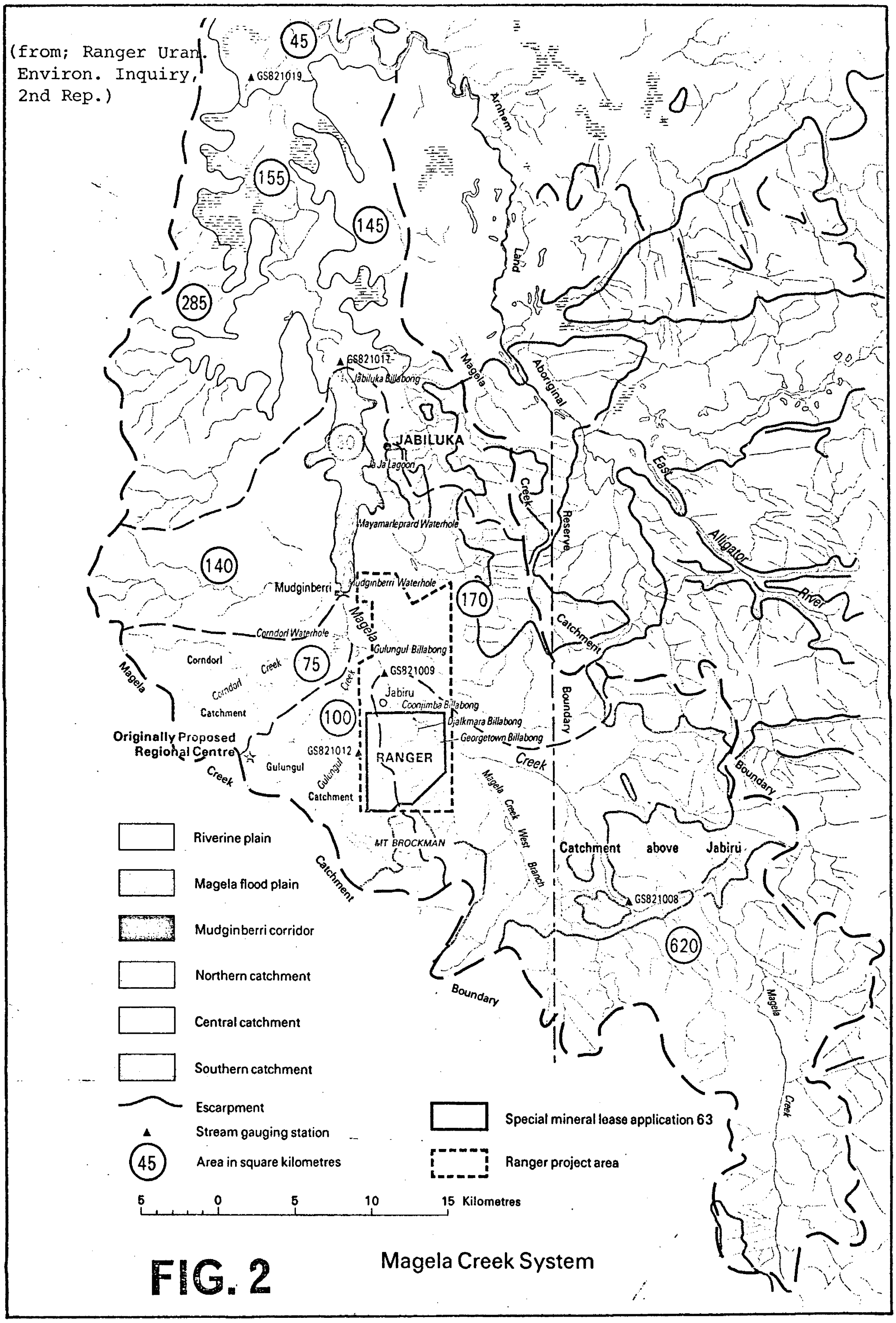
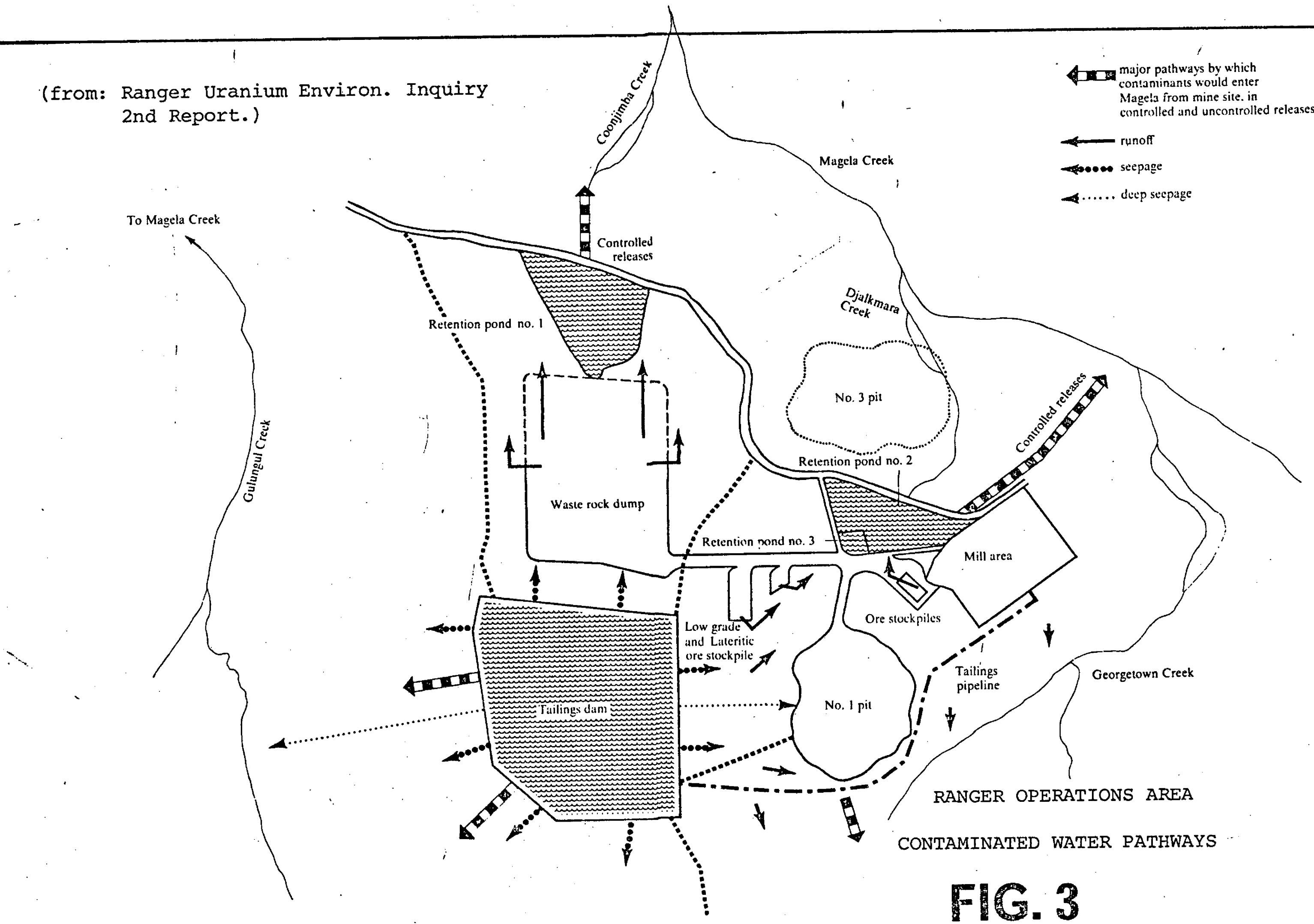


FIG. 2

Magela Creek System

(from: Ranger Uranium Environ. Inquiry
2nd Report.)



RANGER OPERATIONS AREA

CONTAMINATED WATER PATHWAYS

FIG. 3

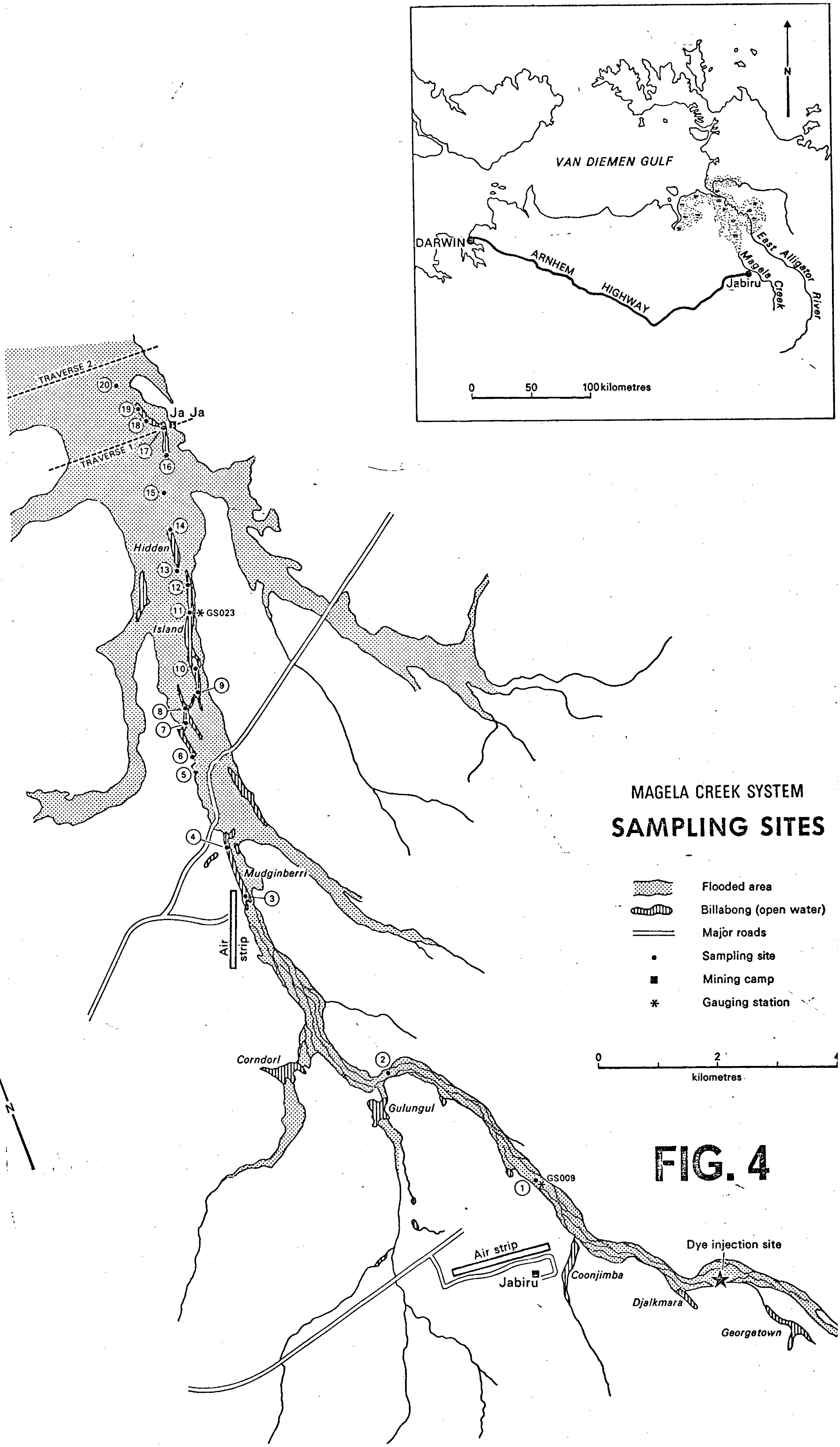
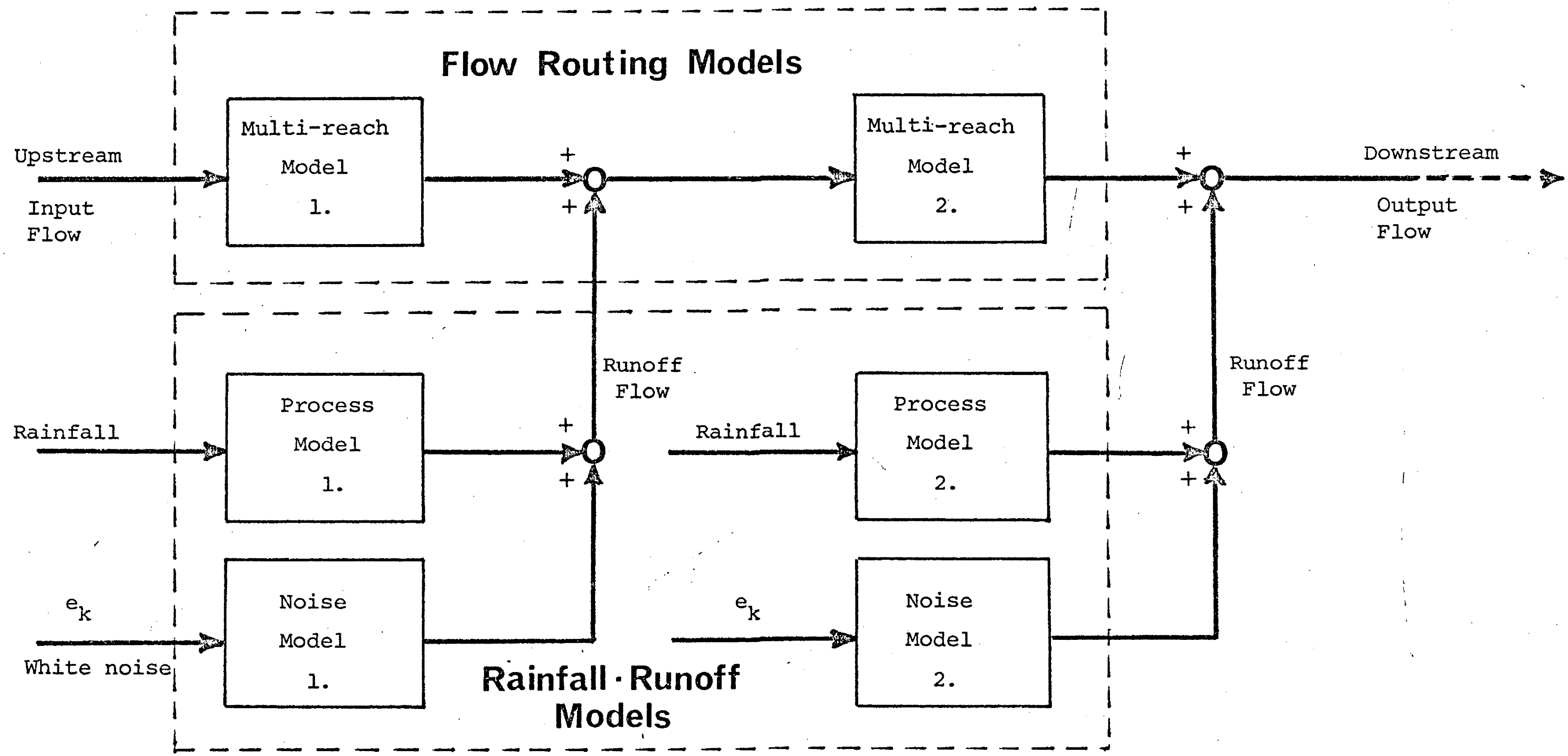

VAN DIEMEN GULF
DARWIN
ARNHEM HIGHWAY
Jabiru
Magela Creek
East Alligator River
N
0 50 100 kilometres
MAGELA CREEK SYSTEM
SAMPLING SITES
Flooded area
Billabong (open water)
Major roads
Sampling site
Mining camp
Gauging station
0 2 4
kilometres
TRAVERSE 2
TRAVERSE 1
Ja Ja
Hidden
Island
GS023
Mudginberri
Air strip
Corndorl
Gulungul
GS009
Air strip
Jabiru
Coonjimba
Djalkmara
Dye injection site
Georgetown
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

FIG. 4



TOTAL STREAMFLOW MODEL

FIG. 5

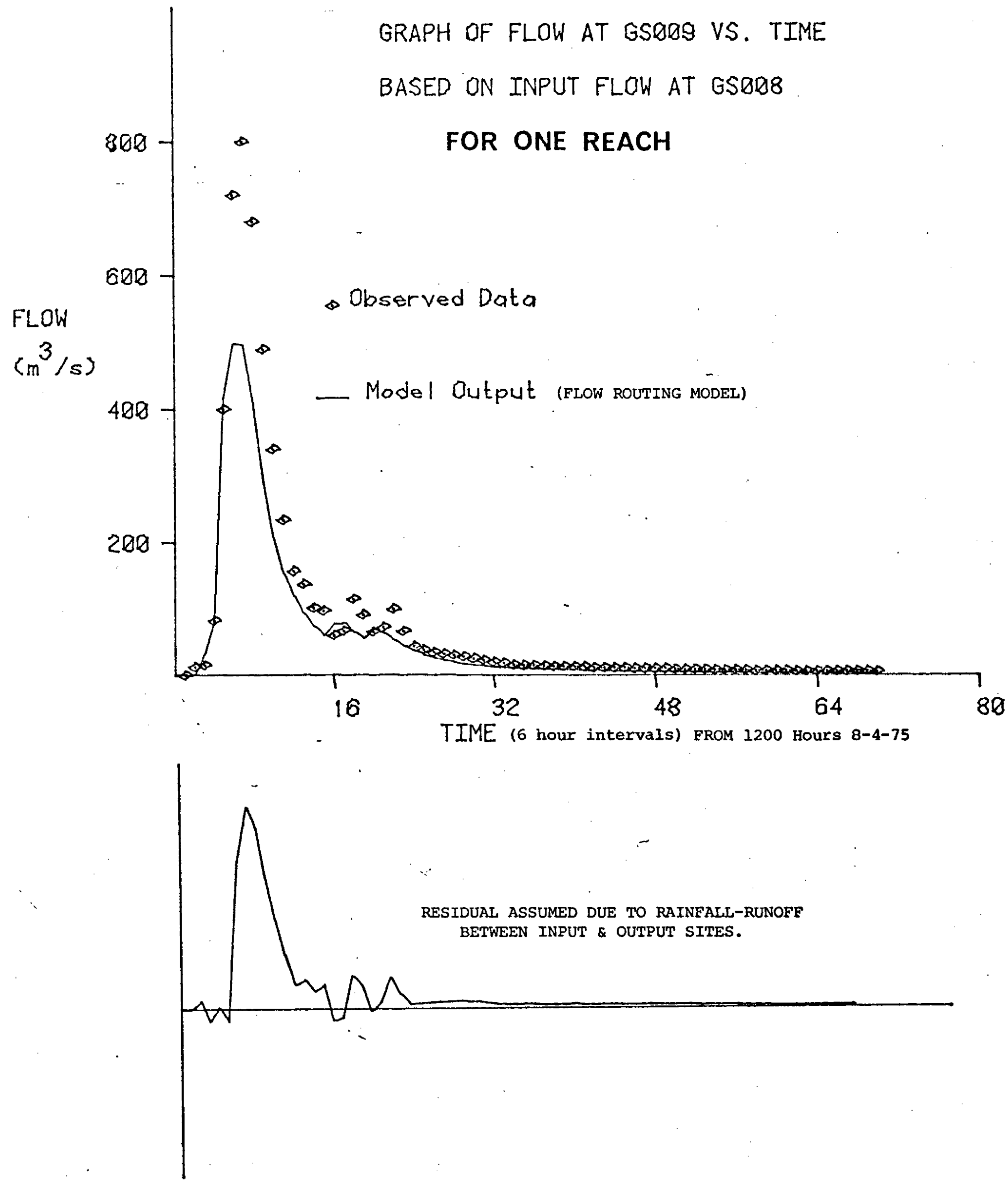

GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
FOR ONE REACH
800
600
400
200
FLOW
(m3/s)
Observed Data
Model Output (FLOW ROUTING MODEL)
16
32
48
64
80
TIME (6 hour intervals) FROM 1200 Hours 8-4-75
RESIDUAL ASSUMED DUE TO RAINFALL-RUNOFF
BETWEEN INPUT & OUTPUT SITES.

FIG. 6a

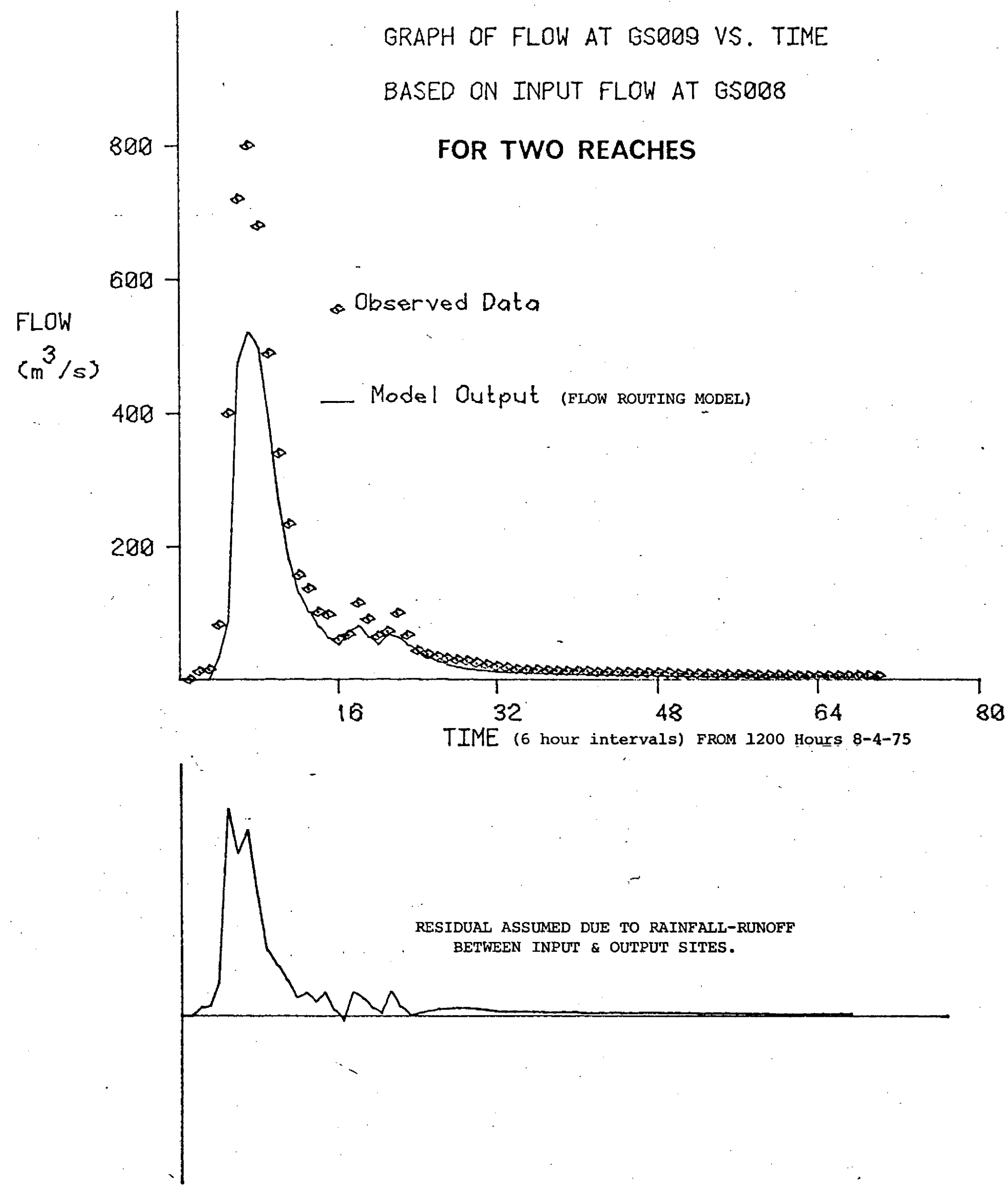

GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
FOR TWO REACHES
800
600
400
200
FLOW
(m³/s)
Observed Data
Model Output (FLOW ROUTING MODEL)
16
32
48
64
80
TIME (6 hour intervals) FROM 1200 Hours 8-4-75
RESIDUAL ASSUMED DUE TO RAINFALL-RUNOFF
BETWEEN INPUT & OUTPUT SITES.

FIG. 6b

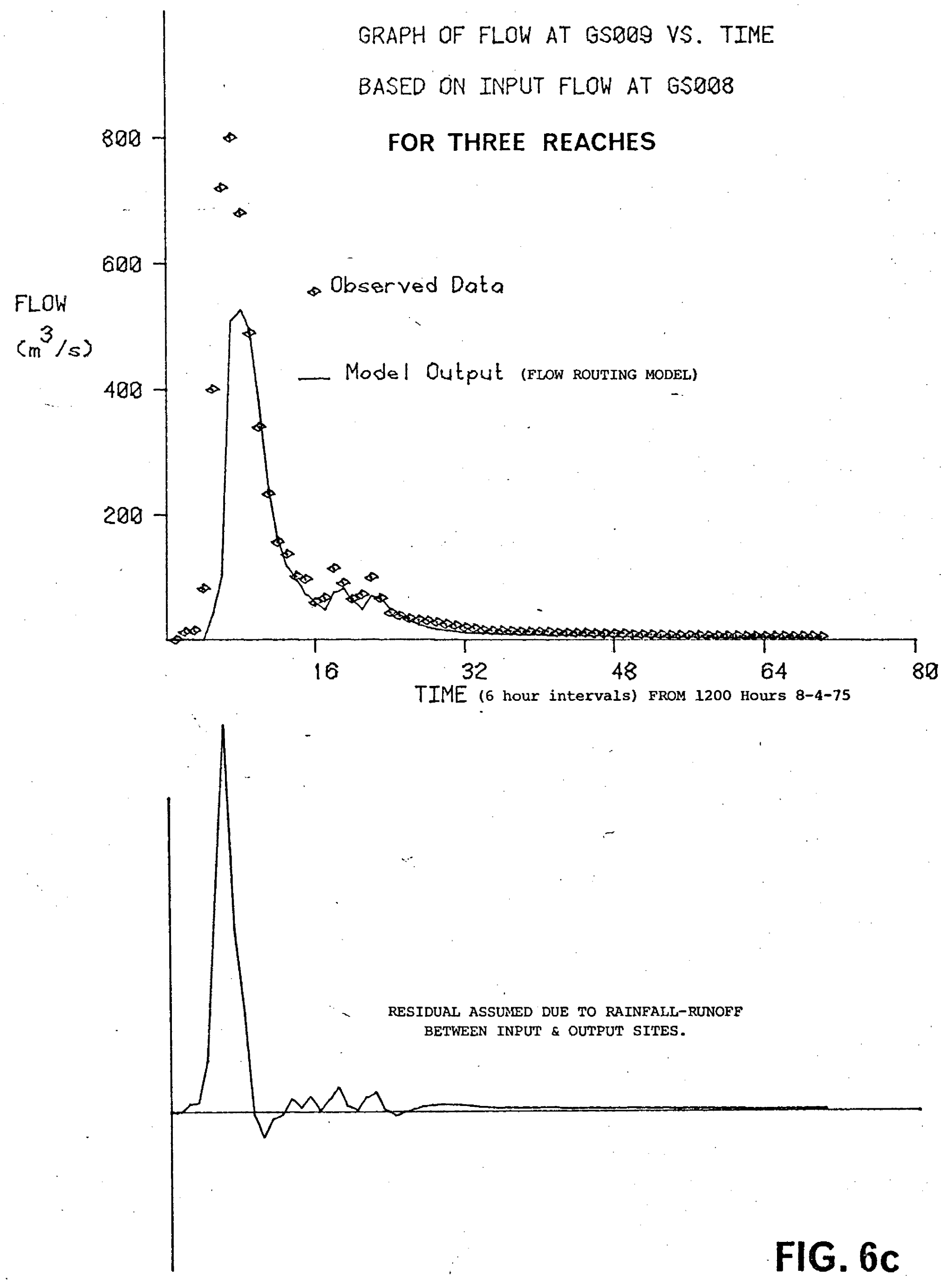
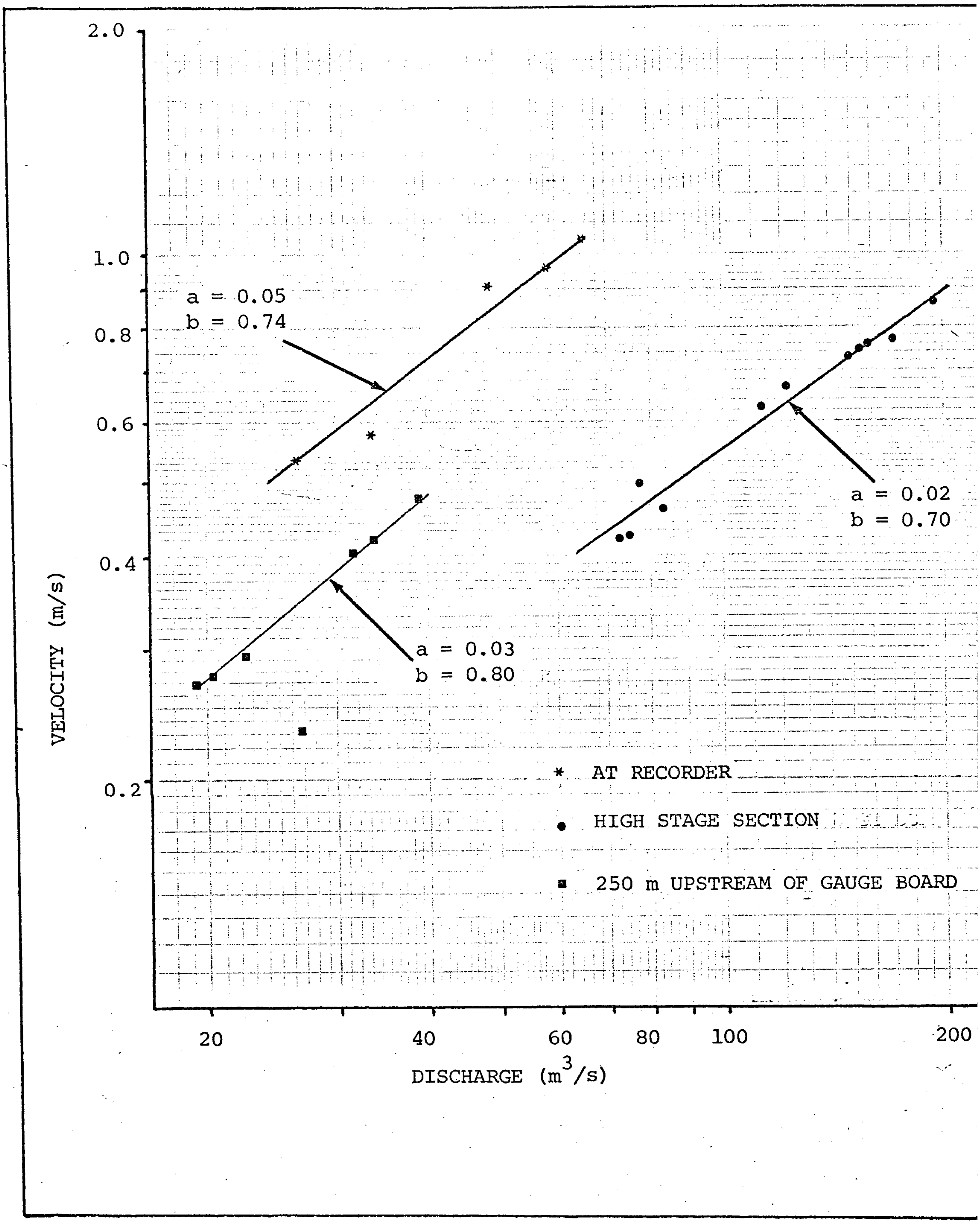

GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
FOR THREE REACHES
Observed Data
Model Output (FLOW ROUTING MODEL)
FLOW
(m3/s)
800
600
400
200
16
32
48
64
80
TIME (6 hour intervals) FROM 1200 Hours 8-4-75
RESIDUAL ASSUMED DUE TO RAINFALL-RUNOFF
BETWEEN INPUT & OUTPUT SITES.

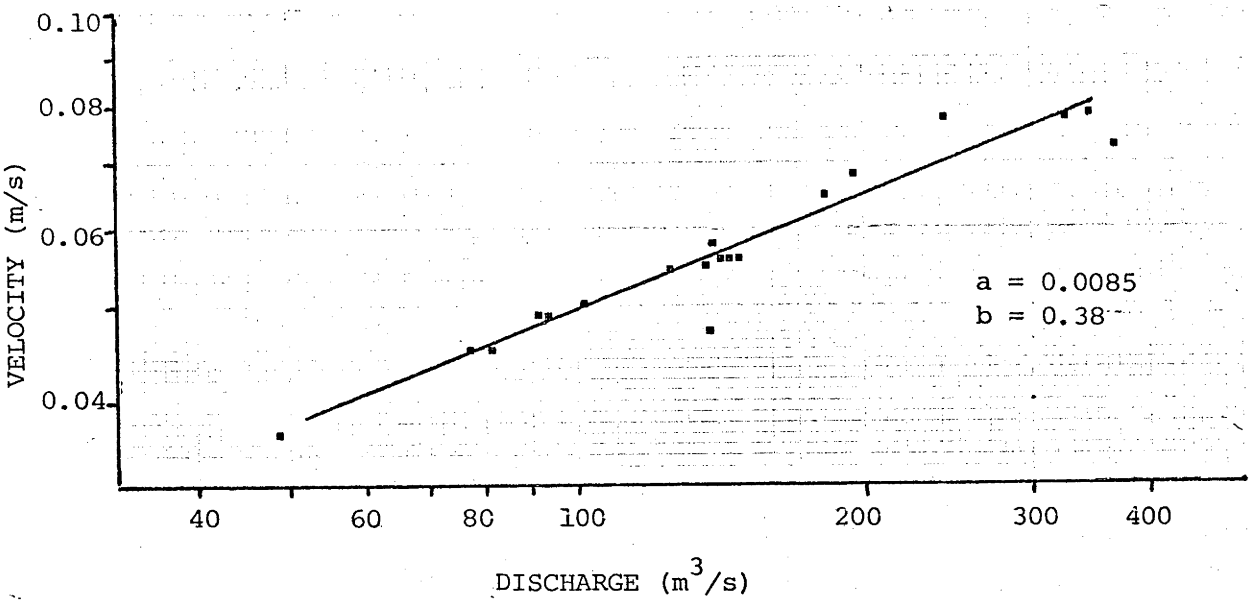
FIG. 6c



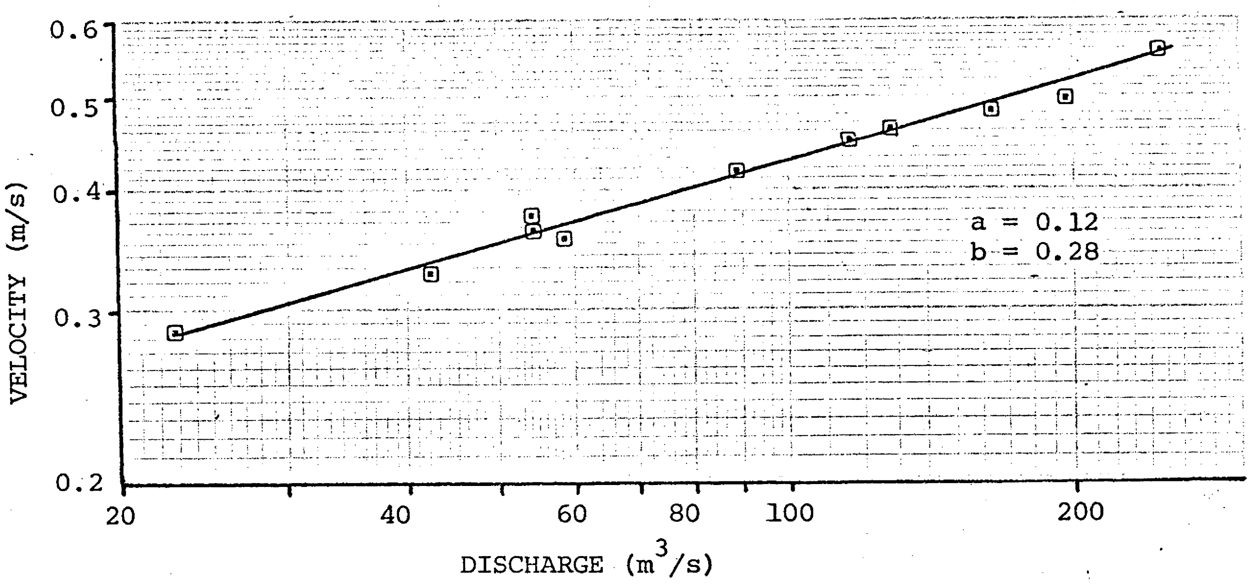
Graphs of Velocity vs. Discharge

(FOR THREE LOCATIONS IN VICINITY OF G.S.821008)

FIG. 7



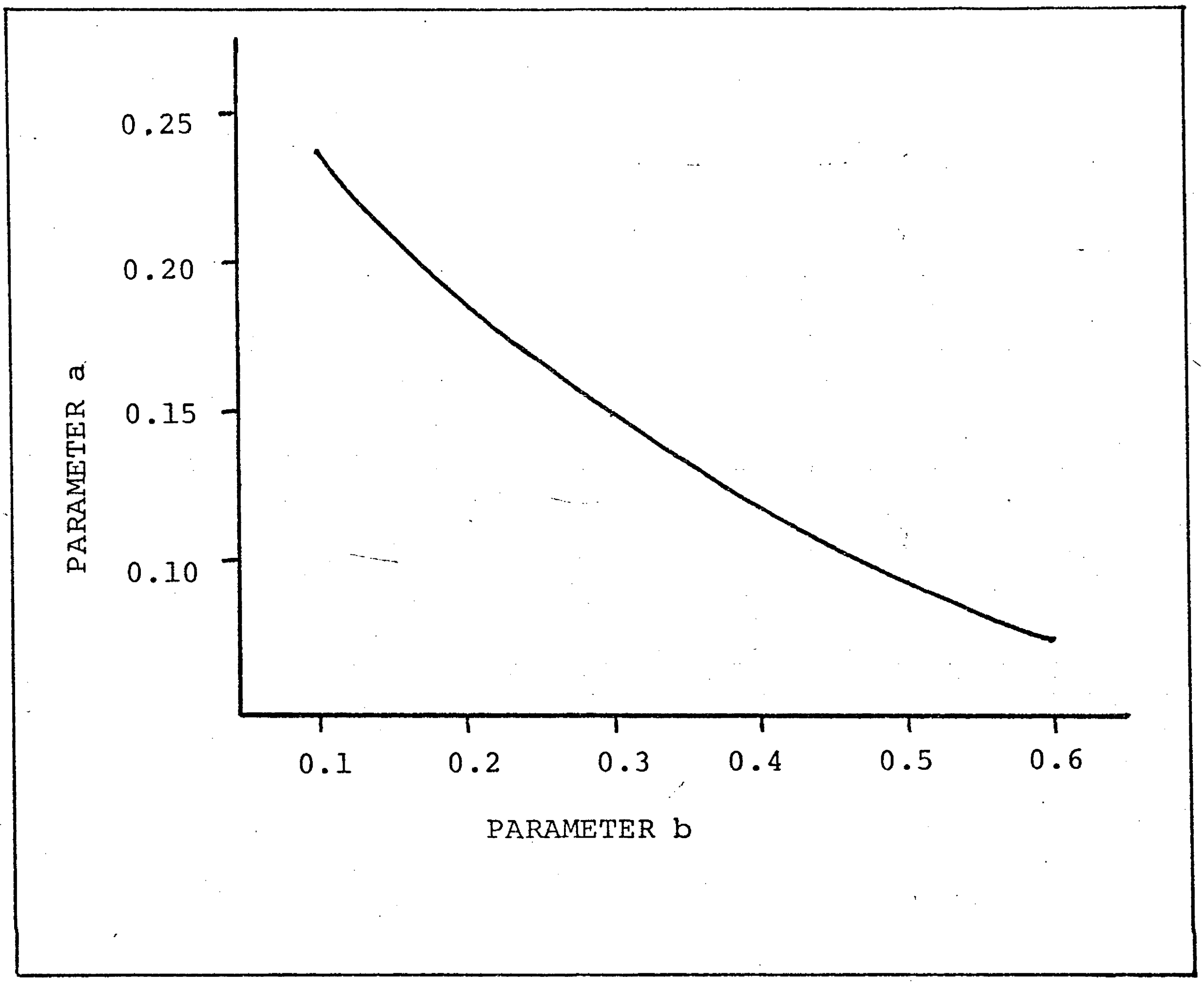
AT GAUGING STATION G.S.821019



AT GAUGING STATION G.S. 821009

Graphs of Velocity vs. Discharge

FIG. 8



Graph of Possible a and b Parameters for Injection Point to Site 2.

FIG. 9

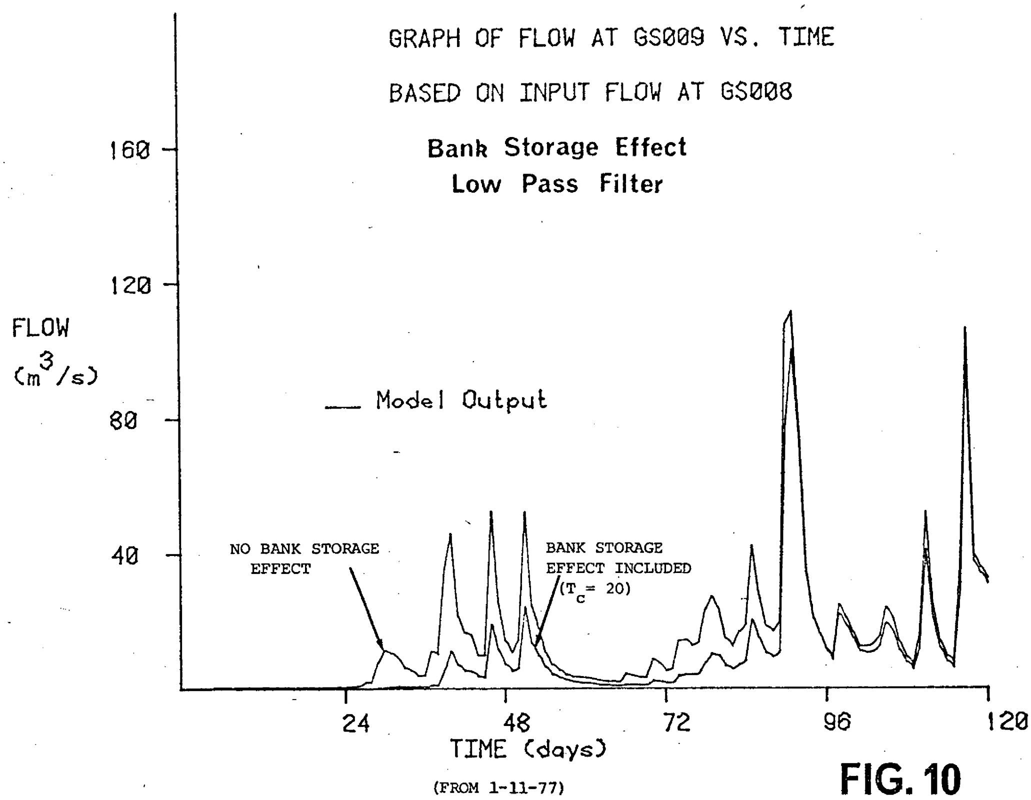

GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
Bank Storage Effect
Low Pass Filter
160
120
80
40
FLOW
(m³/s)
— Model Output
NO BANK STORAGE EFFECT
BANK STORAGE EFFECT INCLUDED
(Tc = 20)
24
48
72
96
120
TIME (days)
(FROM 1-11-77)

FIG. 10

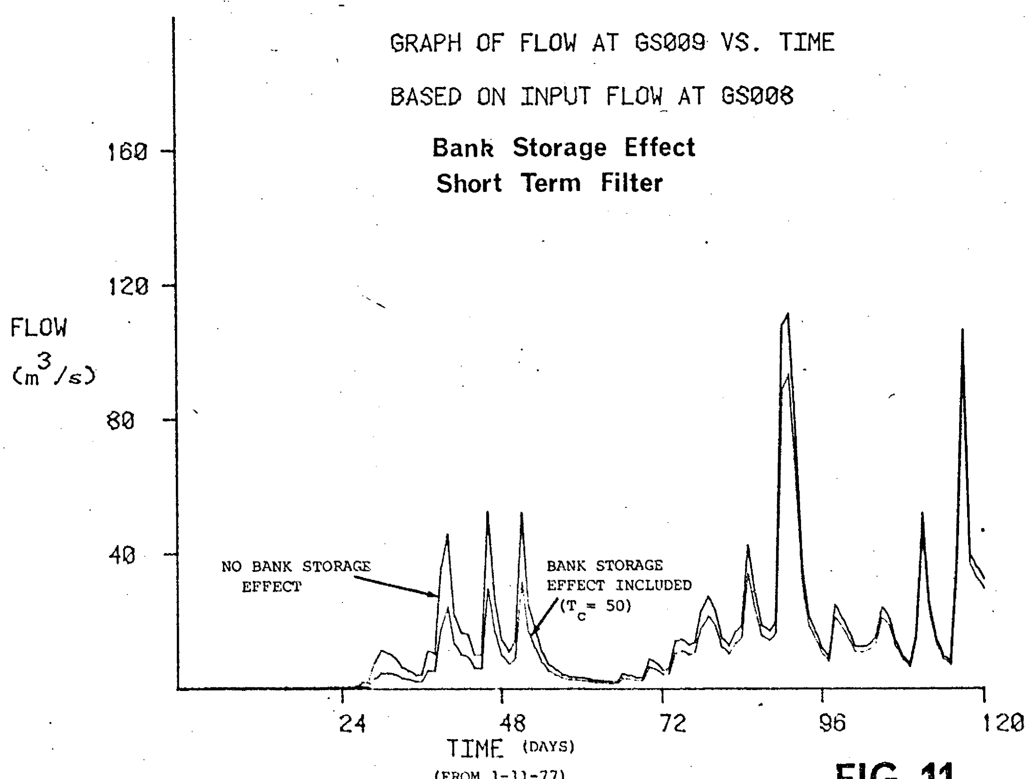
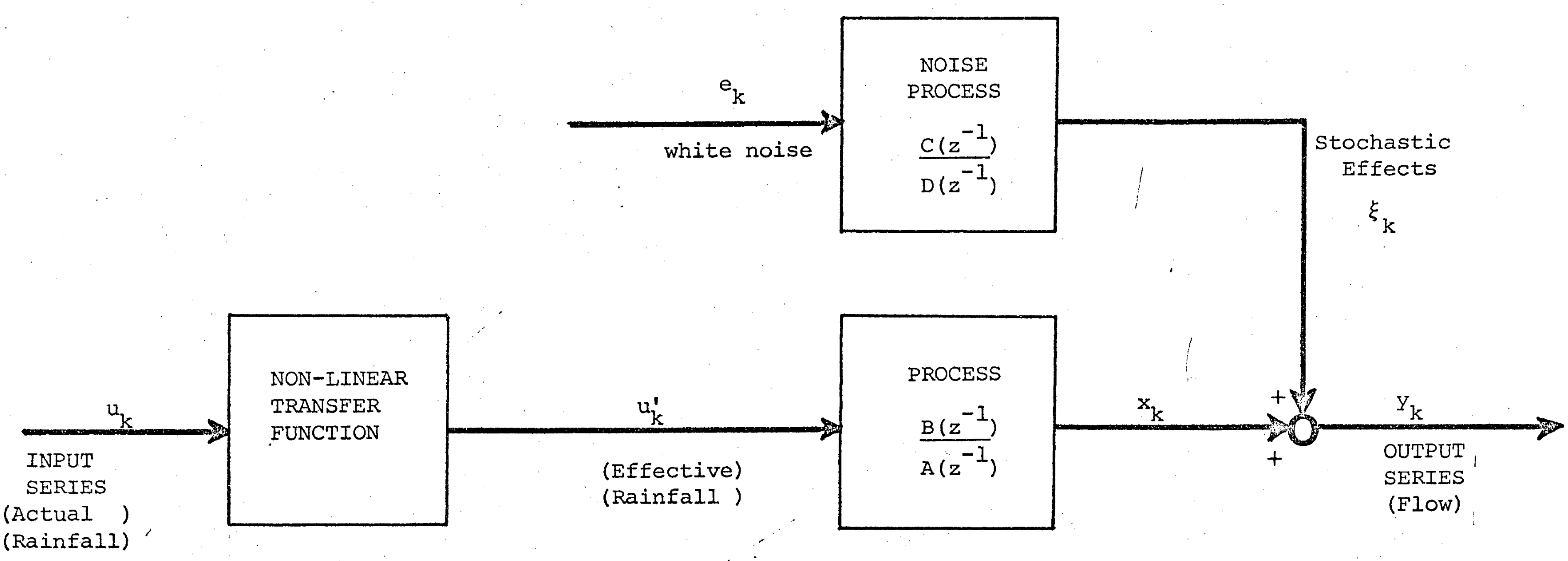
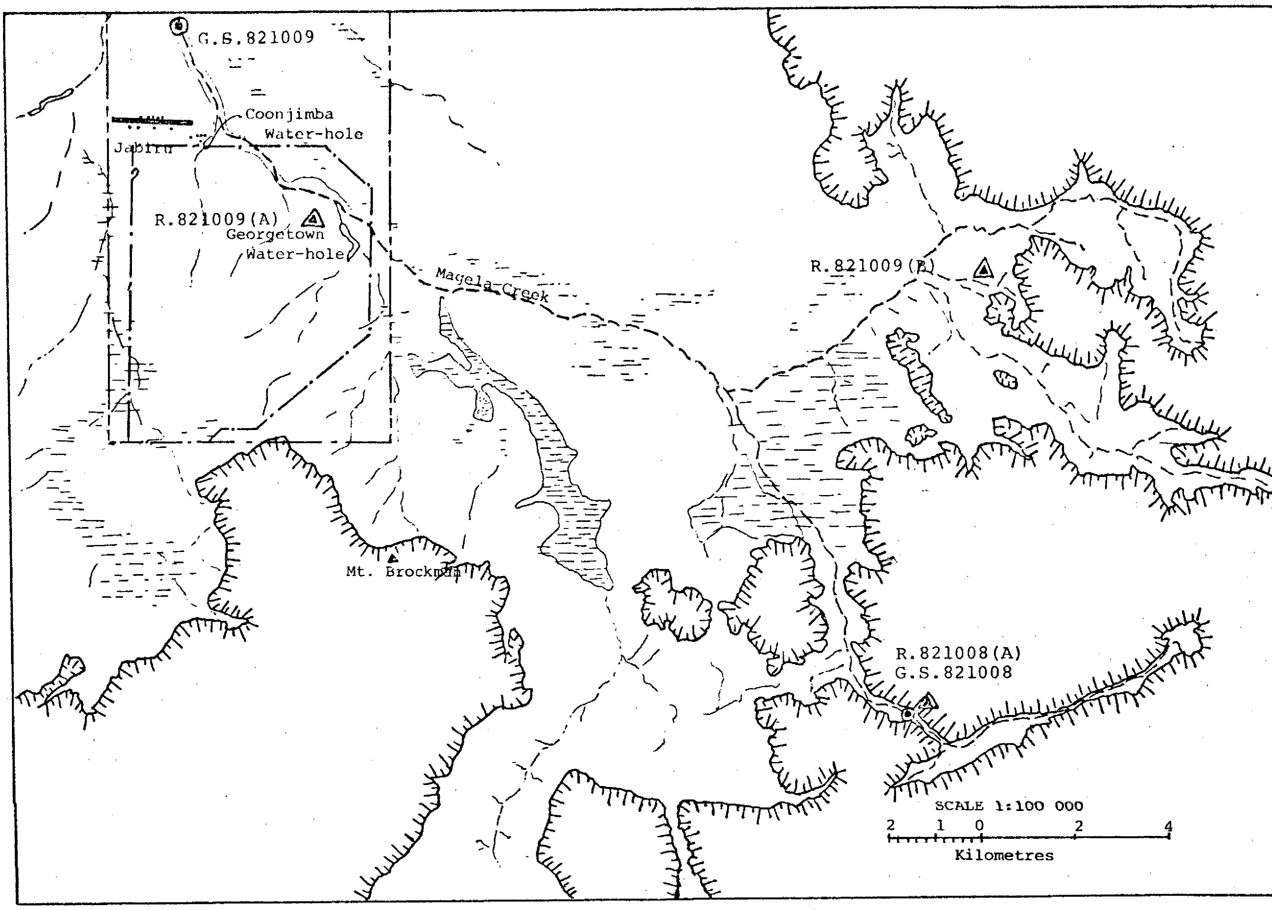

GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
Bank Storage Effect
Short Term Filter
160
120
80
40
FLOW
(m³/s)
NO BANK STORAGE EFFECT
BANK STORAGE EFFECT INCLUDED
(Tc = 50)
24
48
72
96
120
TIME (DAYS)
(FROM 1-11-77)

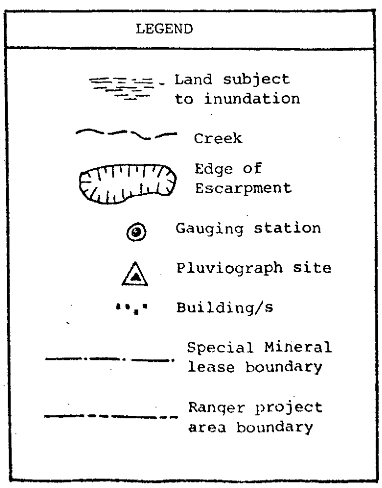
FIG. 11



RAINFALL · RUNOFF MODEL

FIG. 12





Map of Pluviograph Sites between G.S.821008 and G.S.821009

FIG. 13

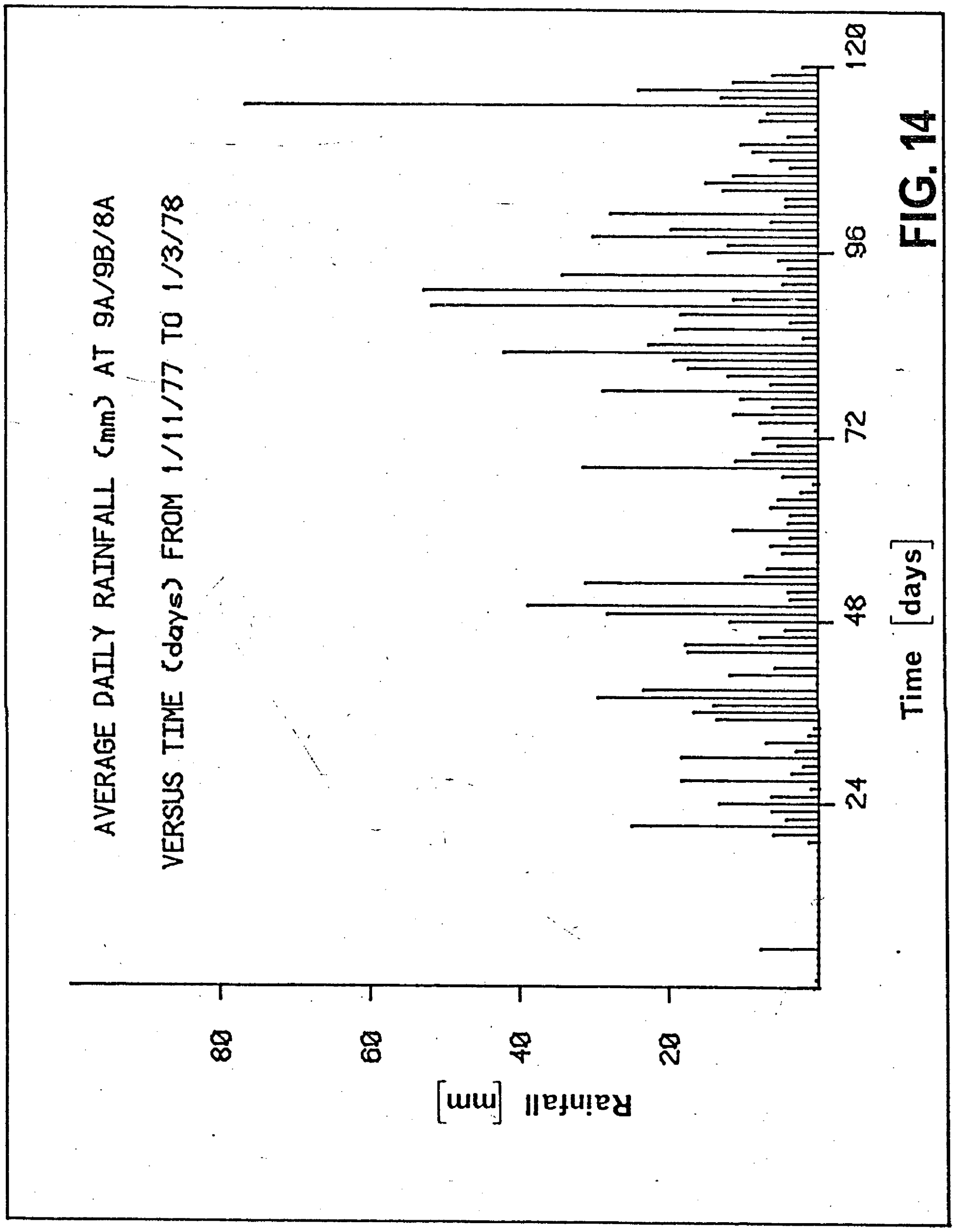

AVERAGE DAILY RAINFALL (mm) AT 9A/9B/8A
VERSUS TIME (days) FROM 1/11/77 TO 1/3/78
Rainfall [mm]
80
60
40
20
24
48
72
96
120
Time [days]

FIG. 14

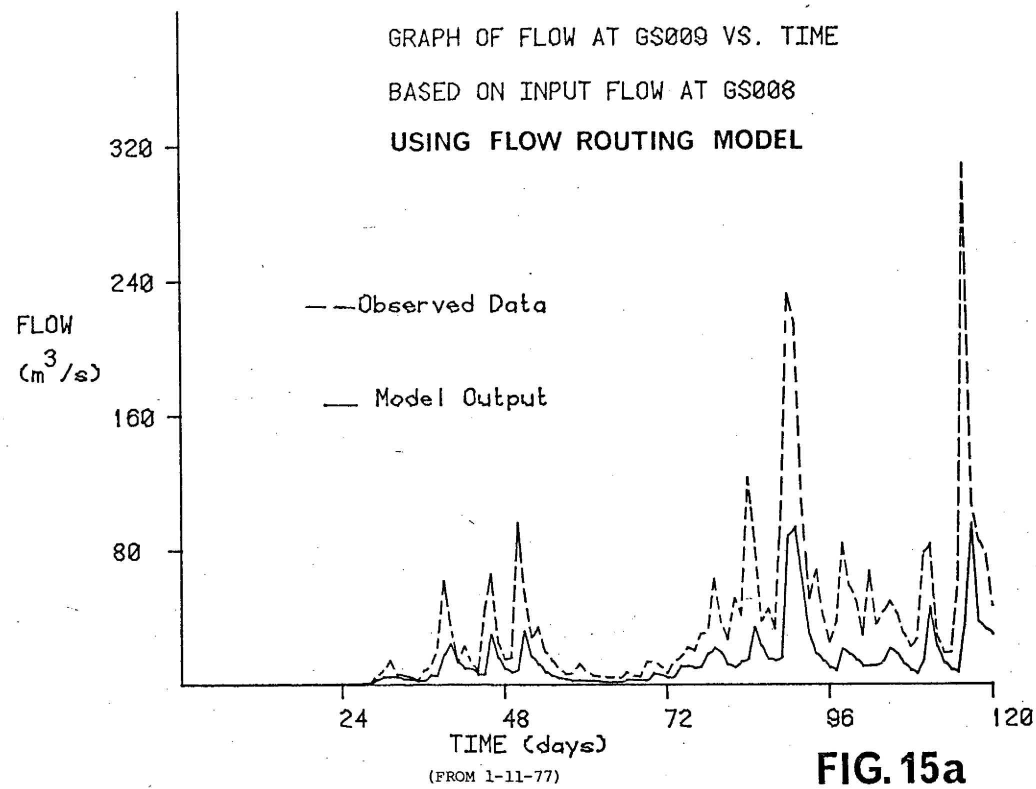


FIG. 15a

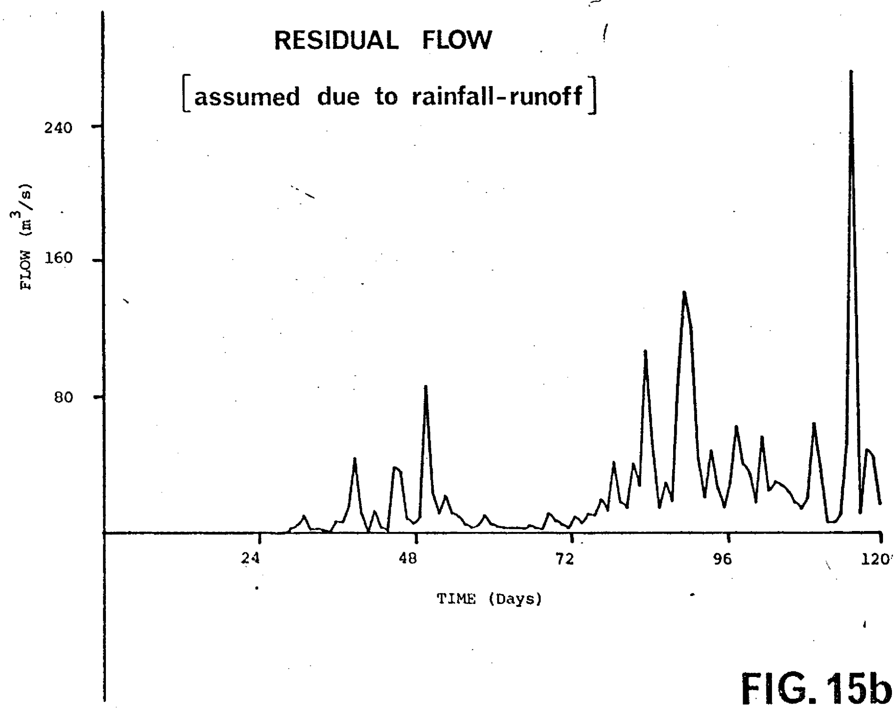


FIG. 15b

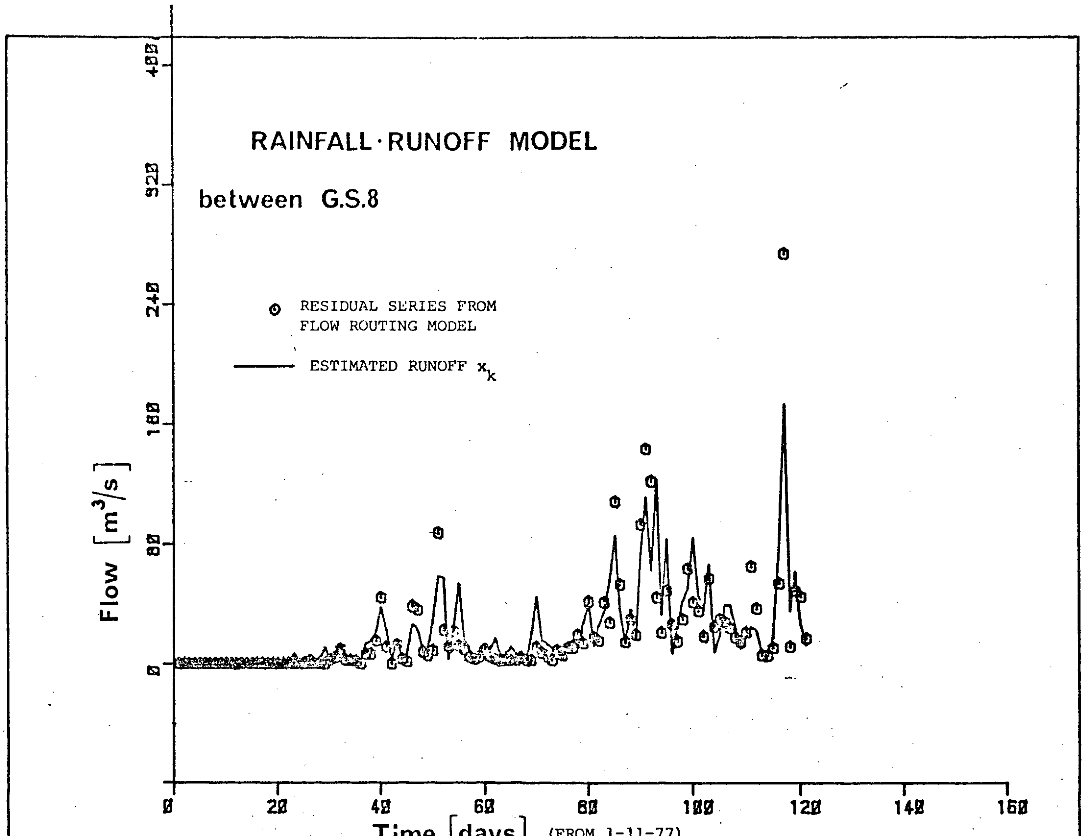

RAINFALL·RUNOFF MODEL
between G.S.8
RESIDUAL SERIES FROM FLOW ROUTING MODEL
ESTIMATED RUNOFF x_k
Flow [m³/s]
Time [days] (FROM 1-11-77)

FIG. 16

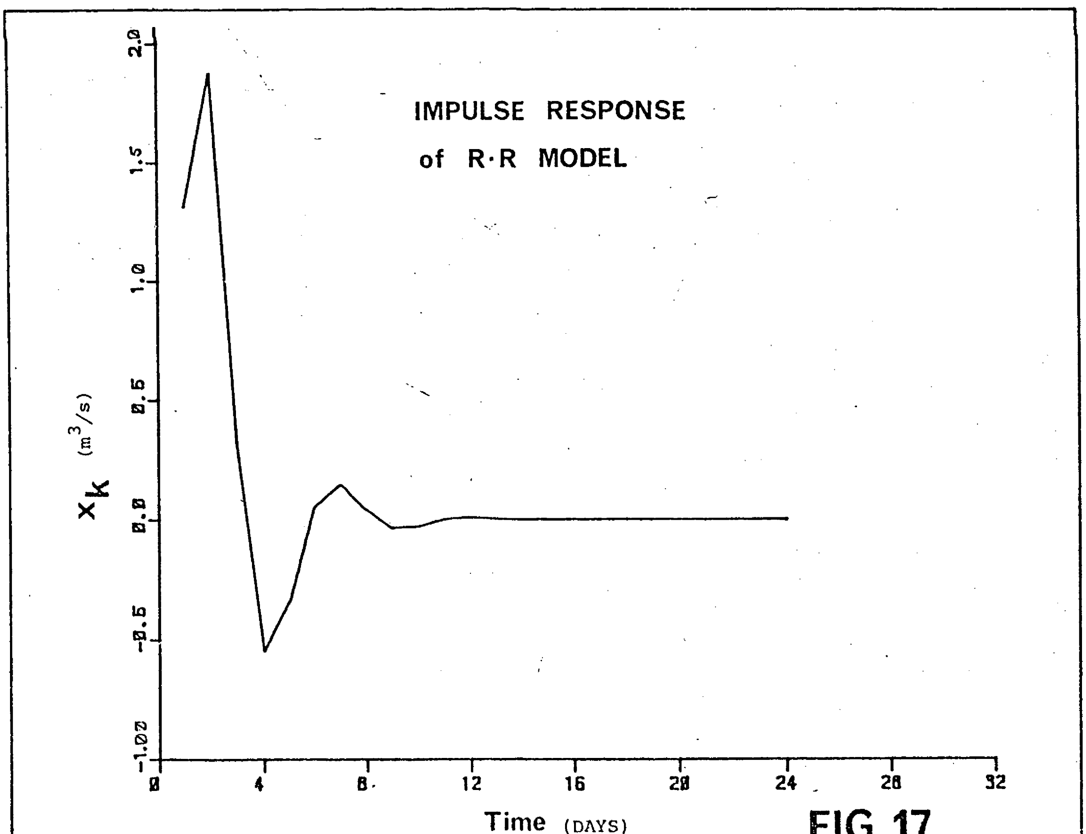

IMPULSE RESPONSE
of R·R MODEL
x_k (m³/s)
Time (DAYS)

FIG. 17

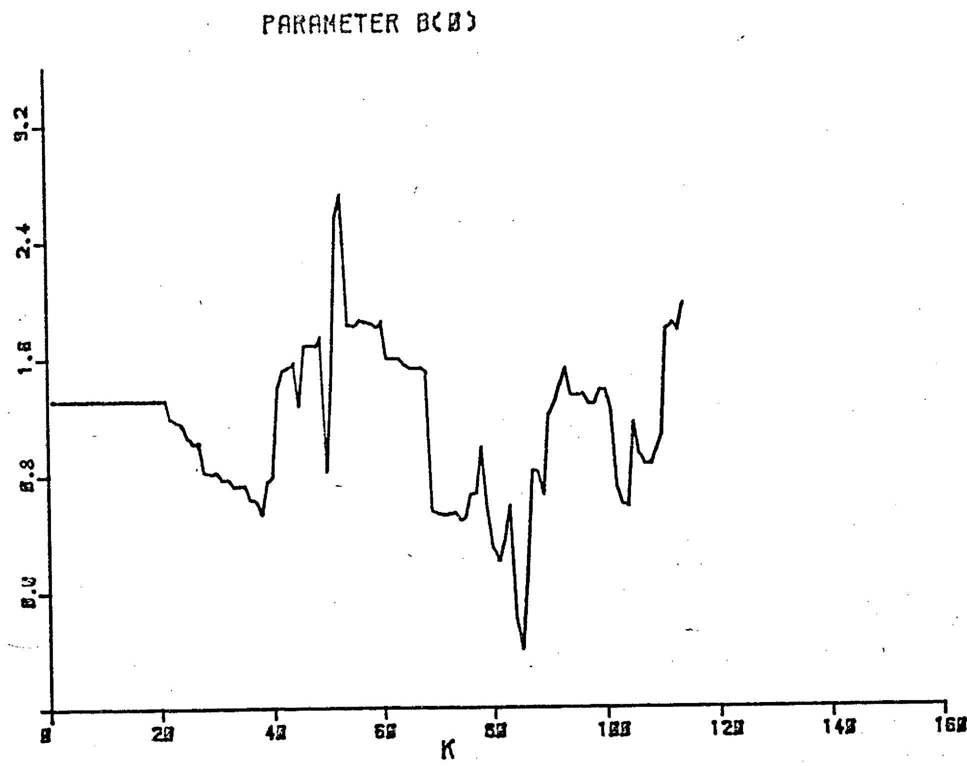


FIG. 18a

RECURSIVE ESTIMATES of b PARAMETERS

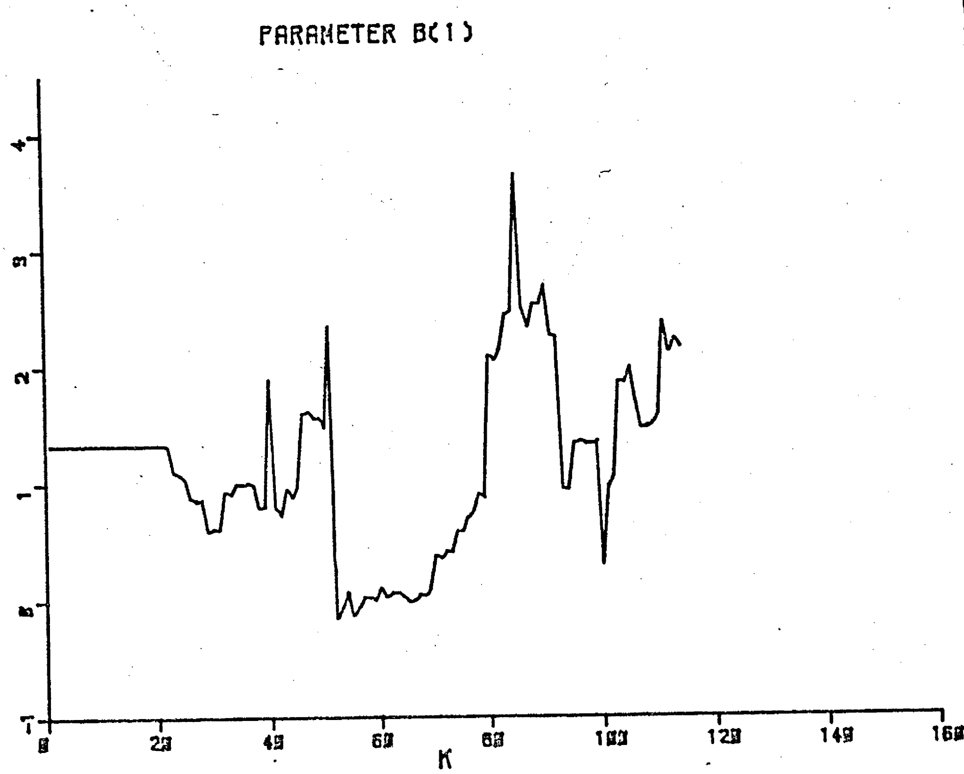


FIG. 18b

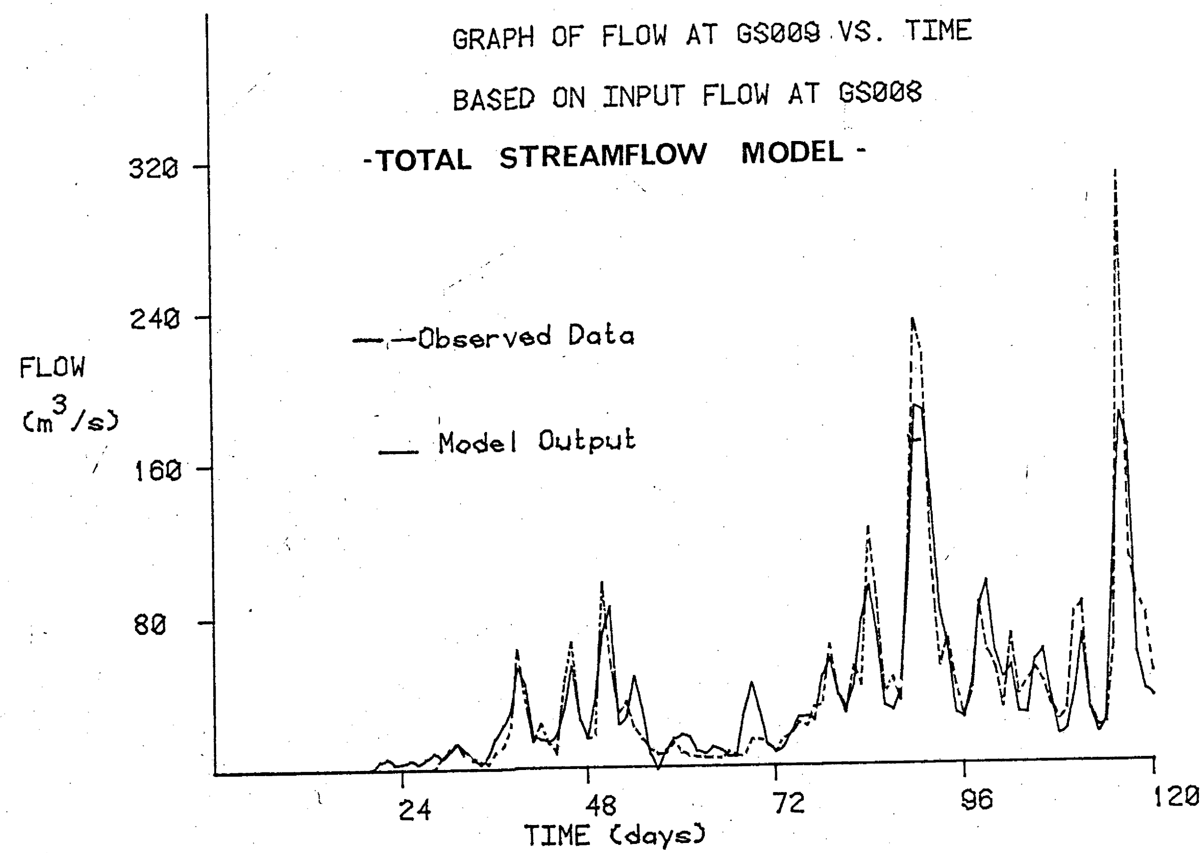

GRAPH OF FLOW AT GS009 VS. TIME
BASED ON INPUT FLOW AT GS008
-TOTAL STREAMFLOW MODEL -
Observed Data
Model Output
FLOW
(m^3/s)
320
240
160
80
24
48
72
96
120
TIME (days)

FIG. 19

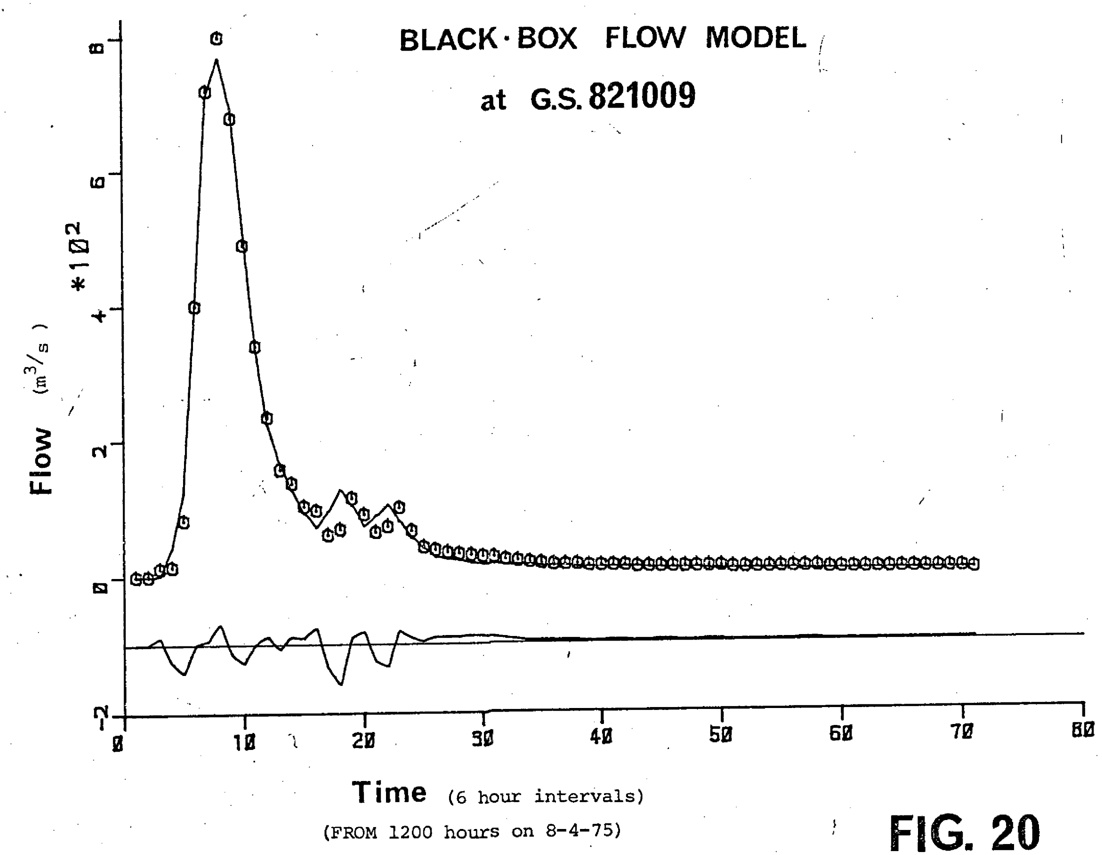

BLACK·BOX FLOW MODEL
at G.S. 821009
Flow (m^3/s) *1Ø2
8
6
4
2
Ø
-2
Ø
1Ø
2Ø
3Ø
4Ø
5Ø
6Ø
7Ø
8Ø
Time (6 hour intervals)
(FROM 1200 hours on 8-4-75)

FIG. 20

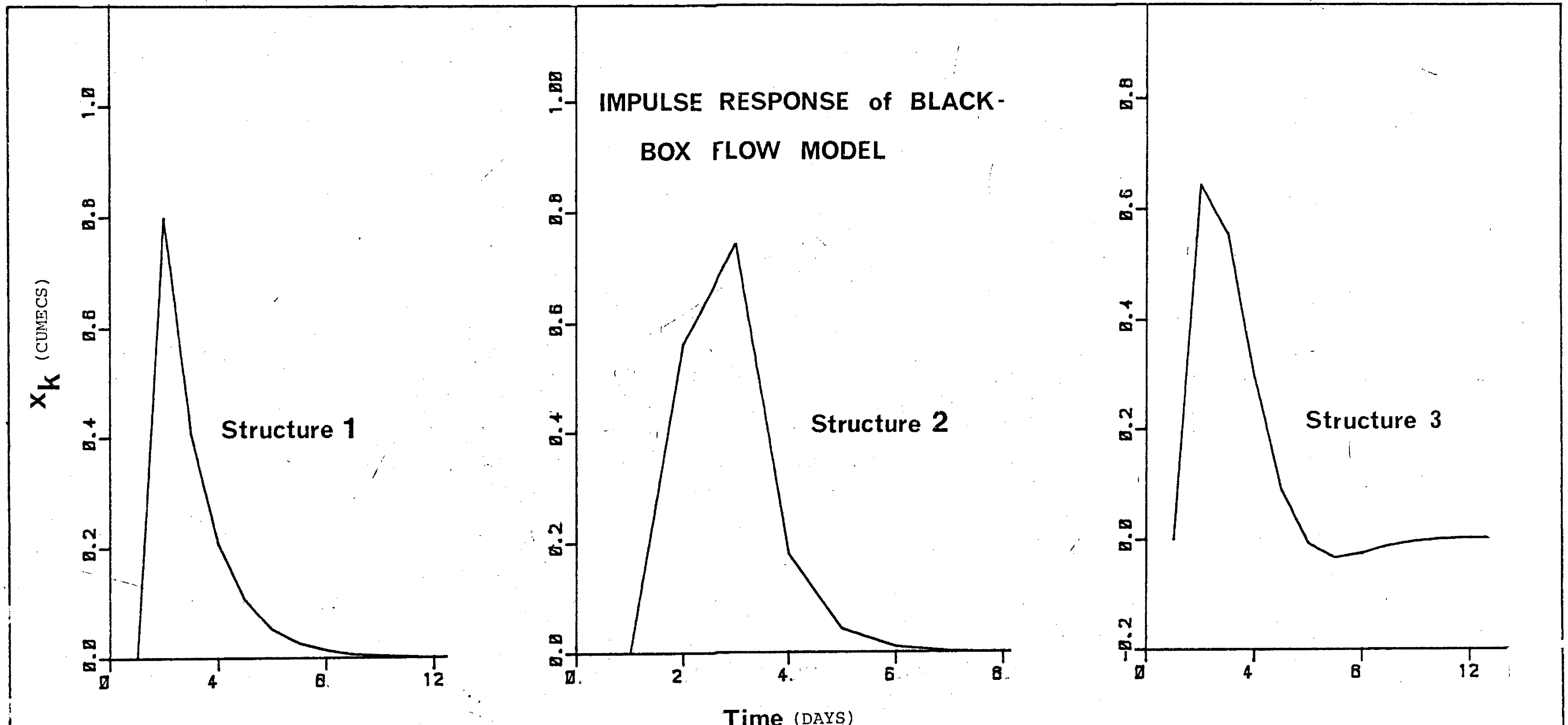
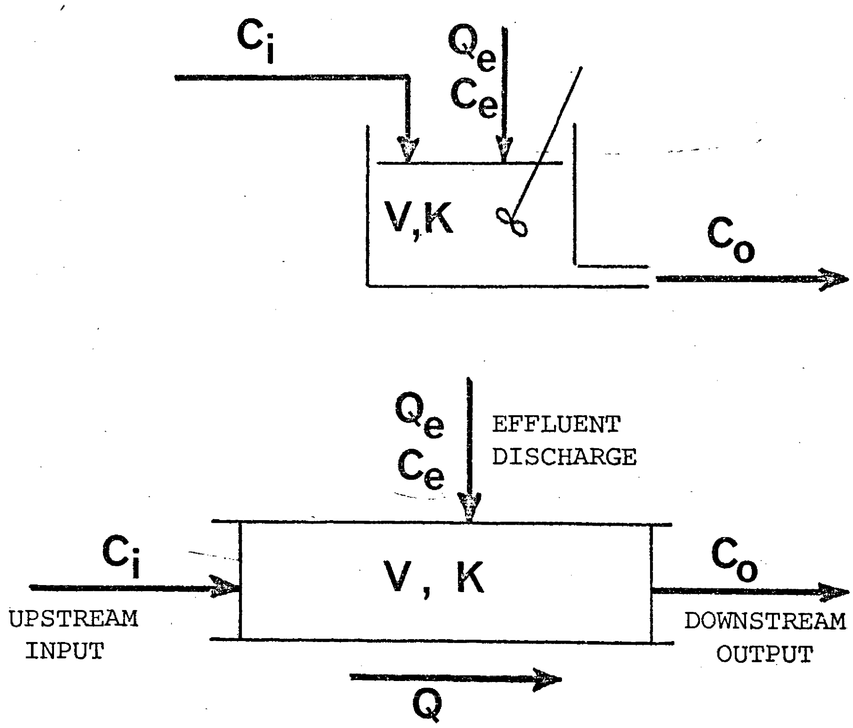

IMPULSE RESPONSE of BLACK-
BOX FLOW MODEL
x_k (CUMECS)
Structure 1
Structure 2
Structure 3
Time (DAYS)
1.0
0.8
0.6
0.4
0.2
0.0
1.00
-0.2
0
2
4
6
8
12

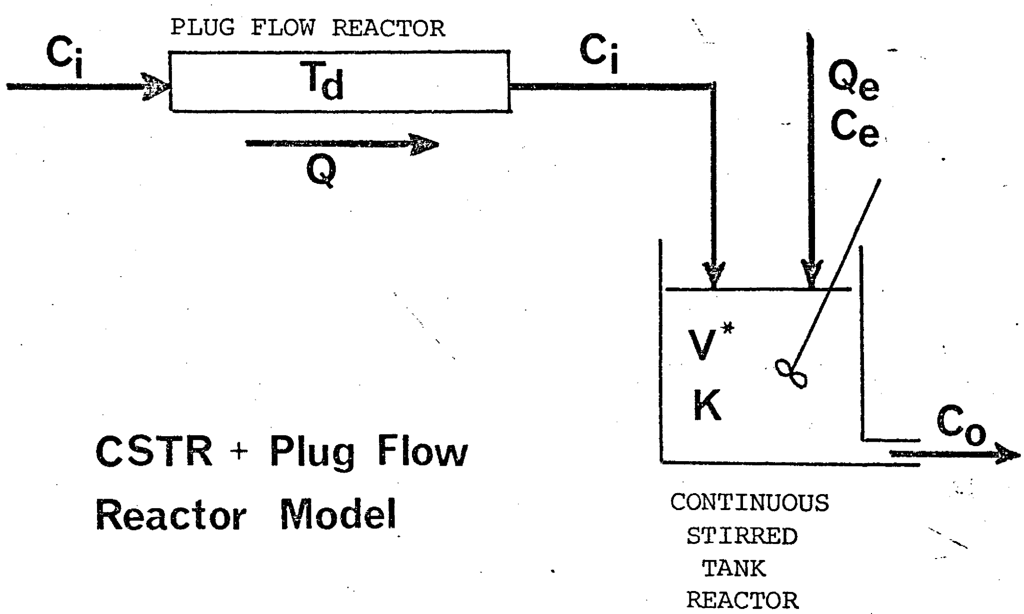
FIG. 21



CSTR Model

SINGLE REACH OF RIVER

FIG. 22a



CSTR + Plug Flow Reactor Model

(ALL VARIABLES ARE AS DEFINED FOR EQUATION)

FIG. 22b

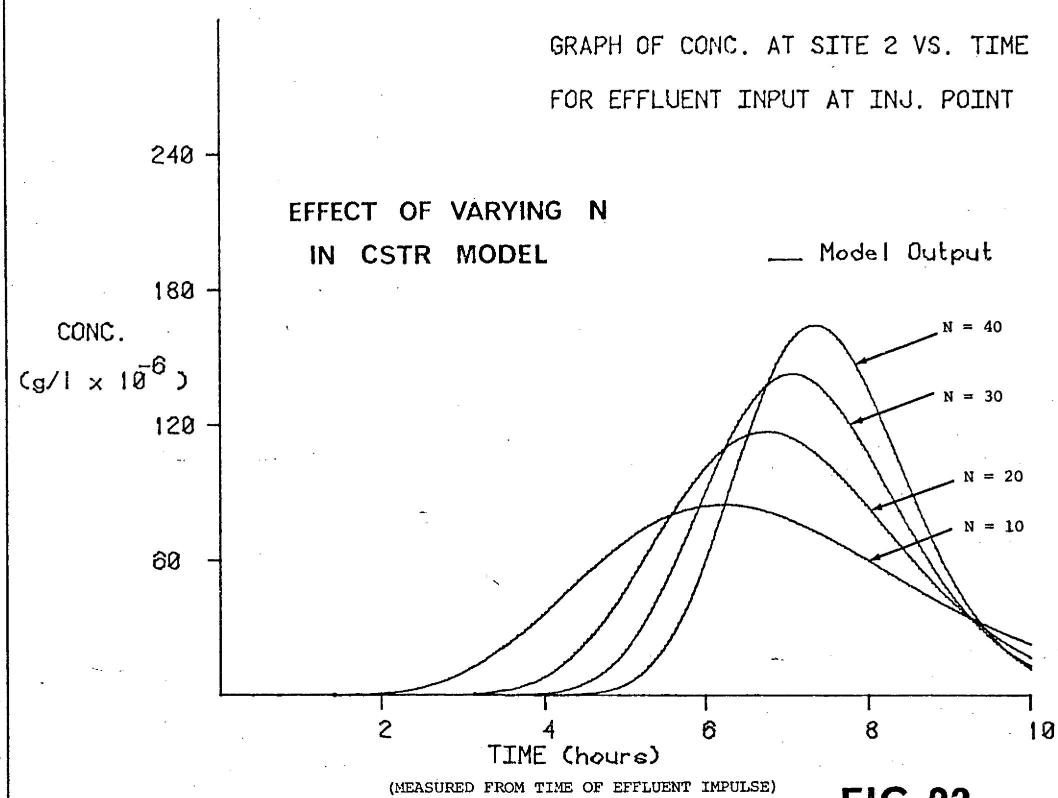

GRAPH OF CONC. AT SITE 2 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
EFFECT OF VARYING N
IN CSTR MODEL
Model Output
N = 40
N = 30
N = 20
N = 10
240
180
120
60
CONC.
(g/l x 10-6)
2
4
6
8
10
TIME (hours)
(MEASURED FROM TIME OF EFFLUENT IMPULSE)

FIG. 23

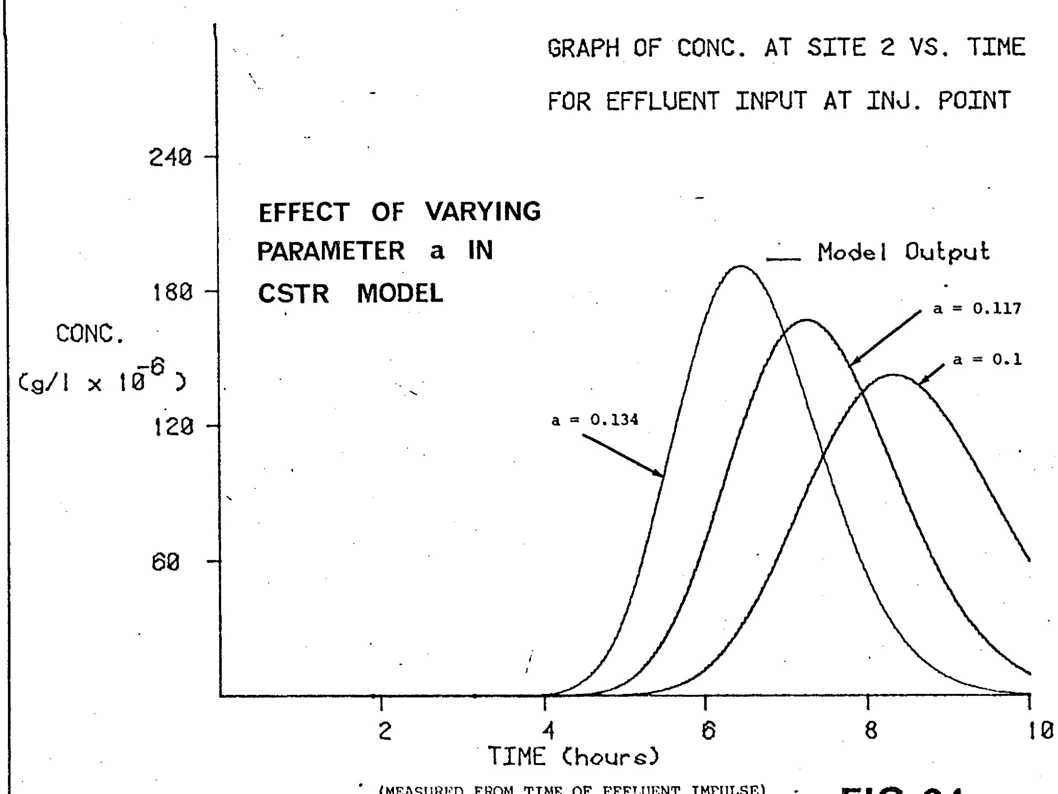
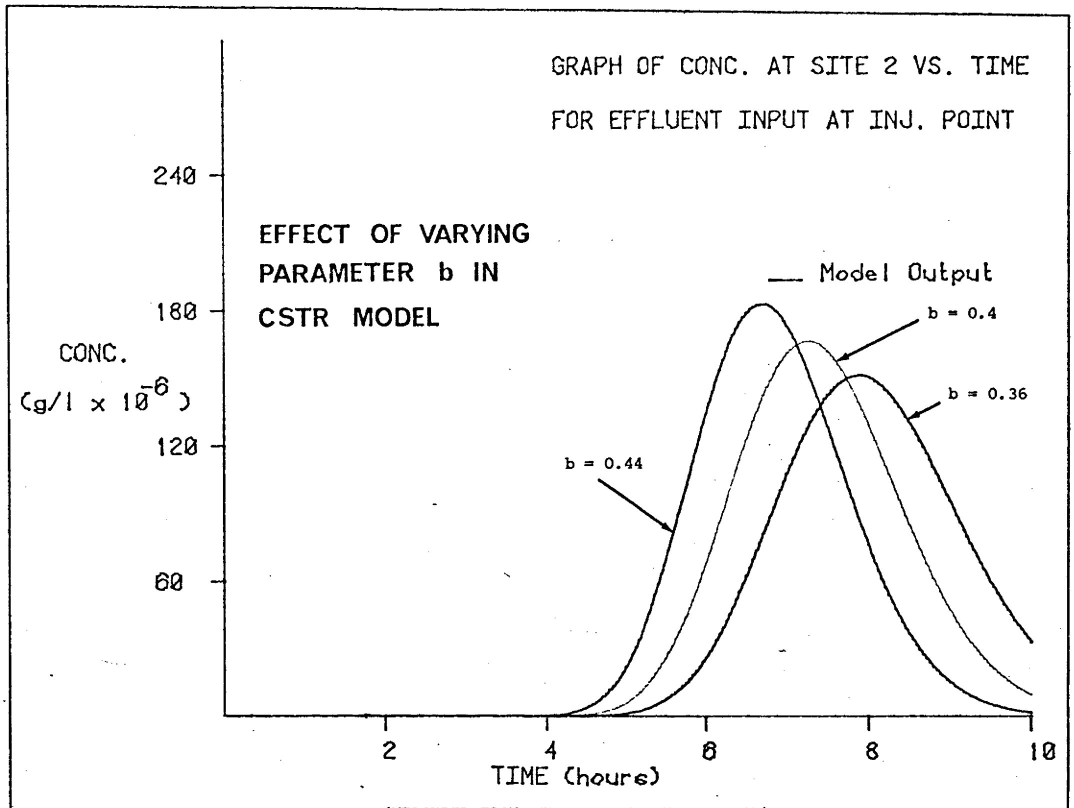
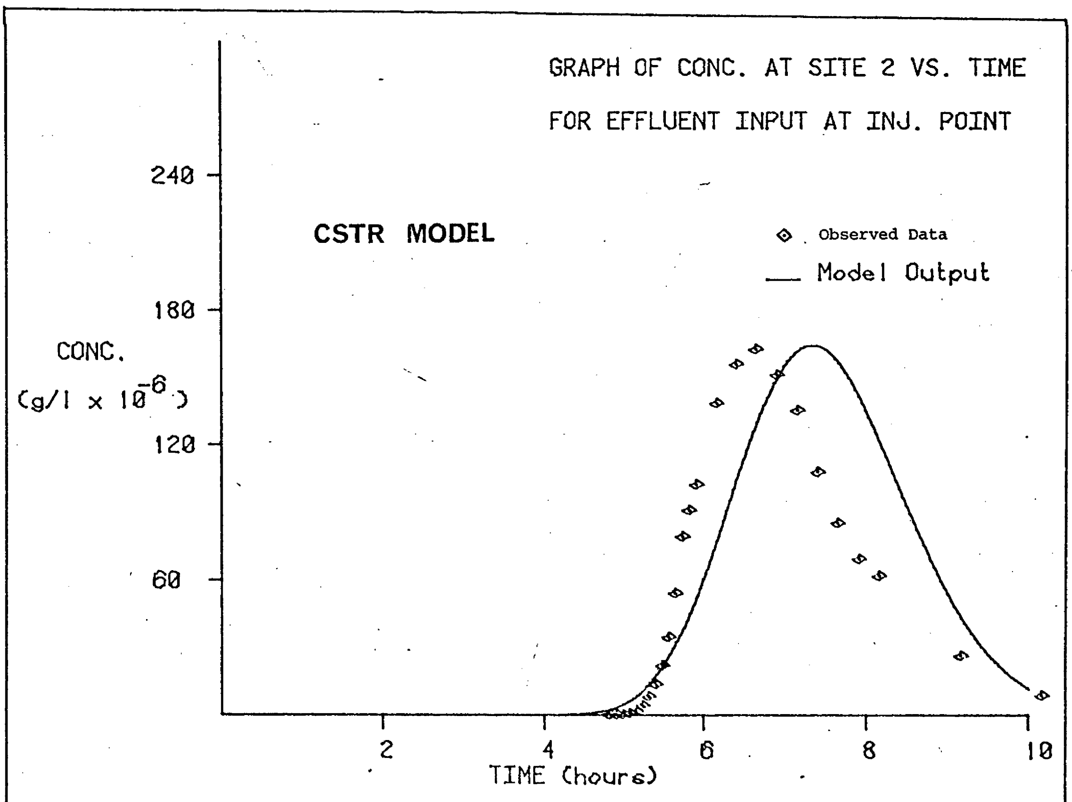

GRAPH OF CONC. AT SITE 2 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
EFFECT OF VARYING
PARAMETER a IN
CSTR MODEL
Model Output
a = 0.117
a = 0.1
a = 0.134
240
180
120
60
CONC.
(g/l x 10-6)
2
4
6
8
10
TIME (hours)
(MEASURED FROM TIME OF EFFLUENT IMPULSE)

FIG. 24



GRAPH OF CONC. AT SITE 2 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
EFFECT OF VARYING PARAMETER b IN CSTR MODEL
Model Output
b = 0.4
b = 0.36
b = 0.44
240
180
120
60
CONC. (g/l x 10^-6)
2
4
6
8
10
TIME (hours)
(MEASURED FROM TIME OF EFFLUENT IMPULSE)

FIG. 25



GRAPH OF CONC. AT SITE 2 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
CSTR MODEL
Observed Data
Model Output
240
180
120
60
CONC. (g/l x 10^-6)
2
4
6
8
10
TIME (hours)
(MEASURED FROM TIME OF EFFLUENT IMPULSE)

FIG. 26

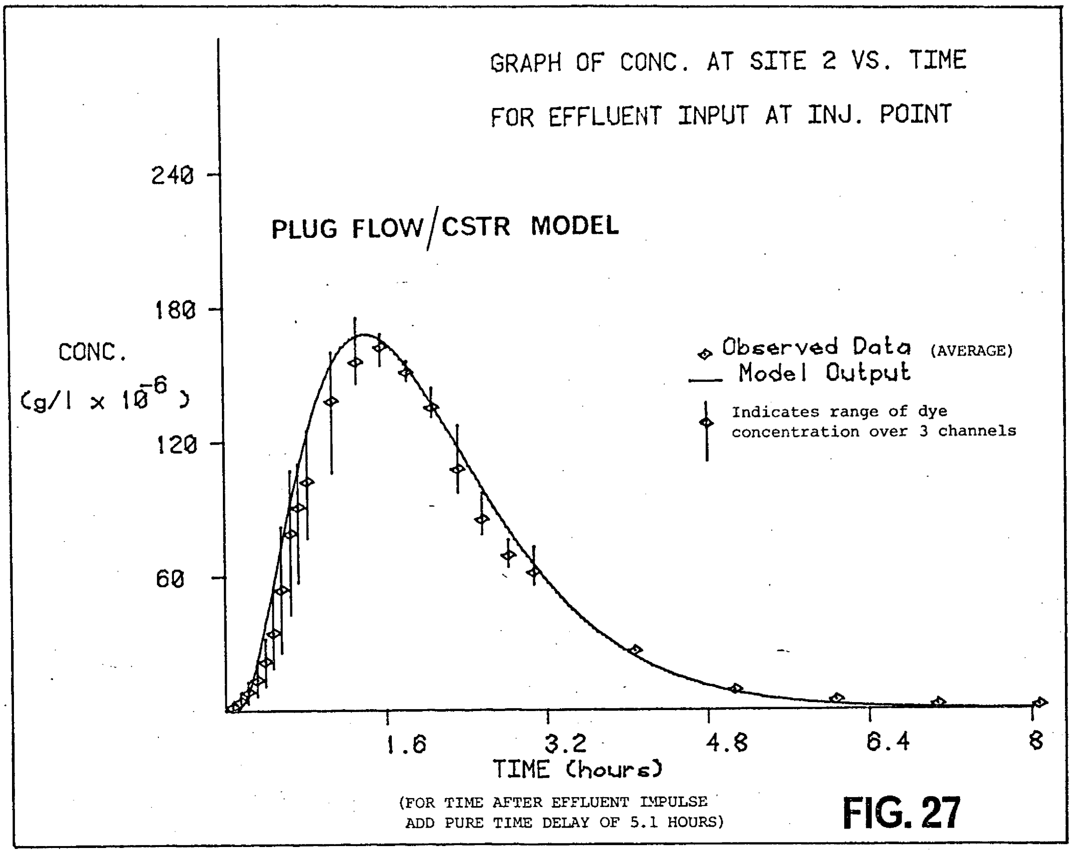

GRAPH OF CONC. AT SITE 2 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
PLUG FLOW/CSTR MODEL
240
180
120
60
CONC.
(g/l x 10⁻⁶)
Observed Data (AVERAGE)
Model Output
Indicates range of dye concentration over 3 channels
1.6
3.2
4.8
6.4
8
TIME (hours)
(FOR TIME AFTER EFFLUENT IMPULSE ADD PURE TIME DELAY OF 5.1 HOURS)

FIG. 27

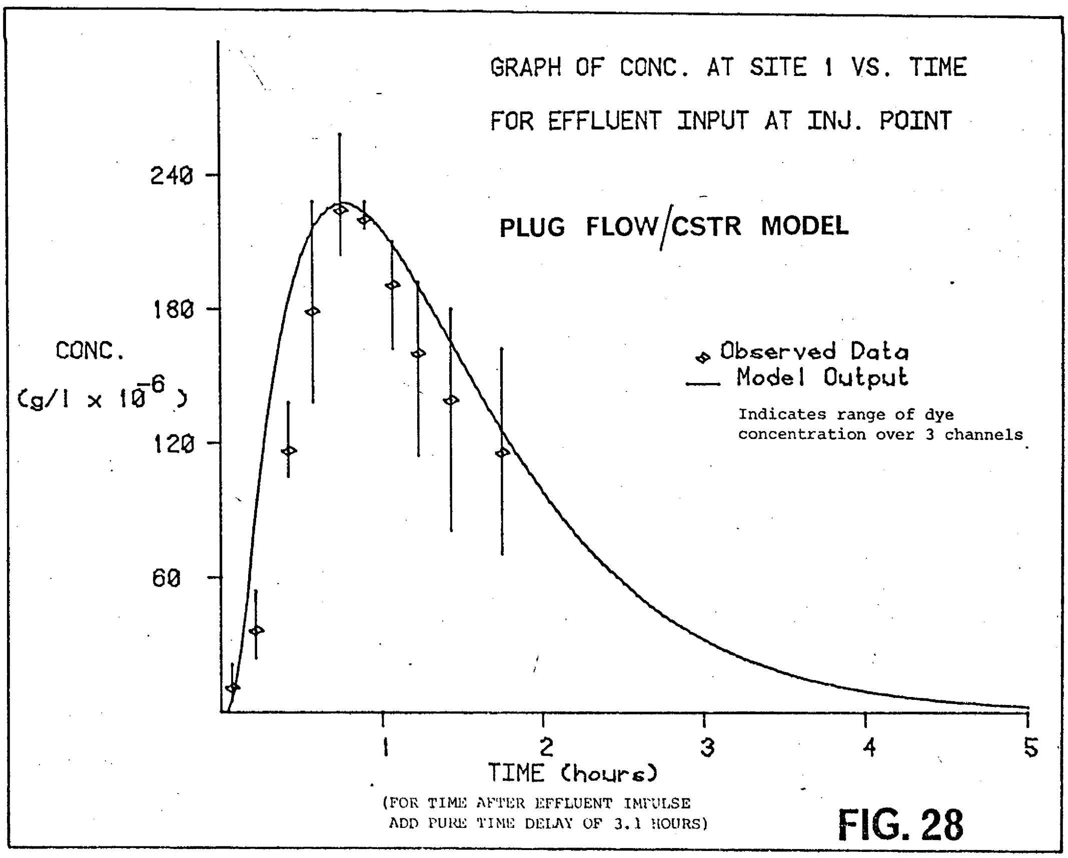
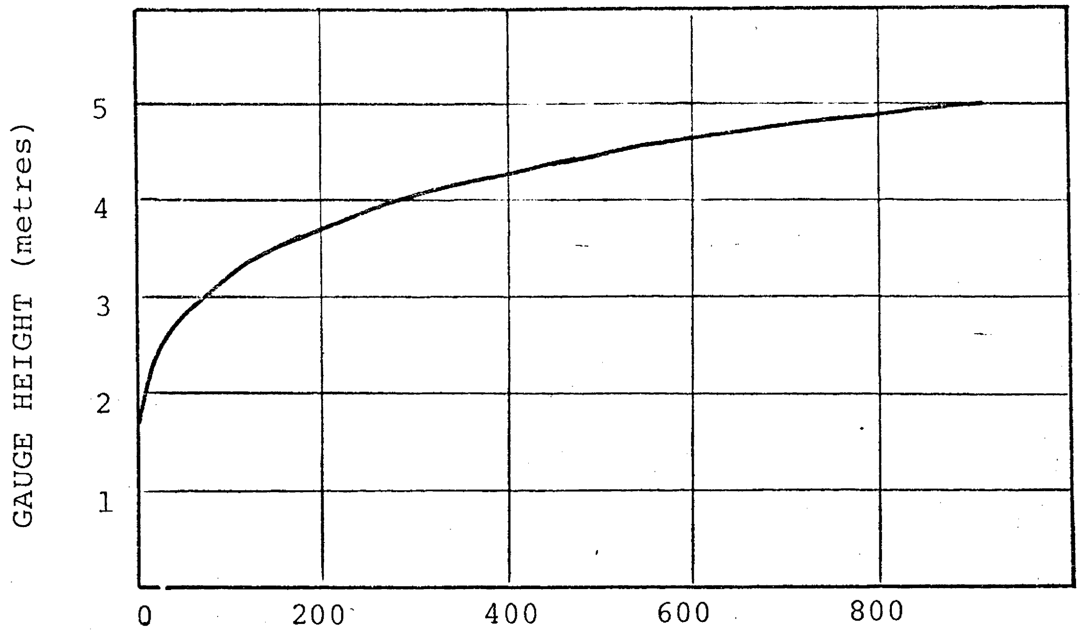
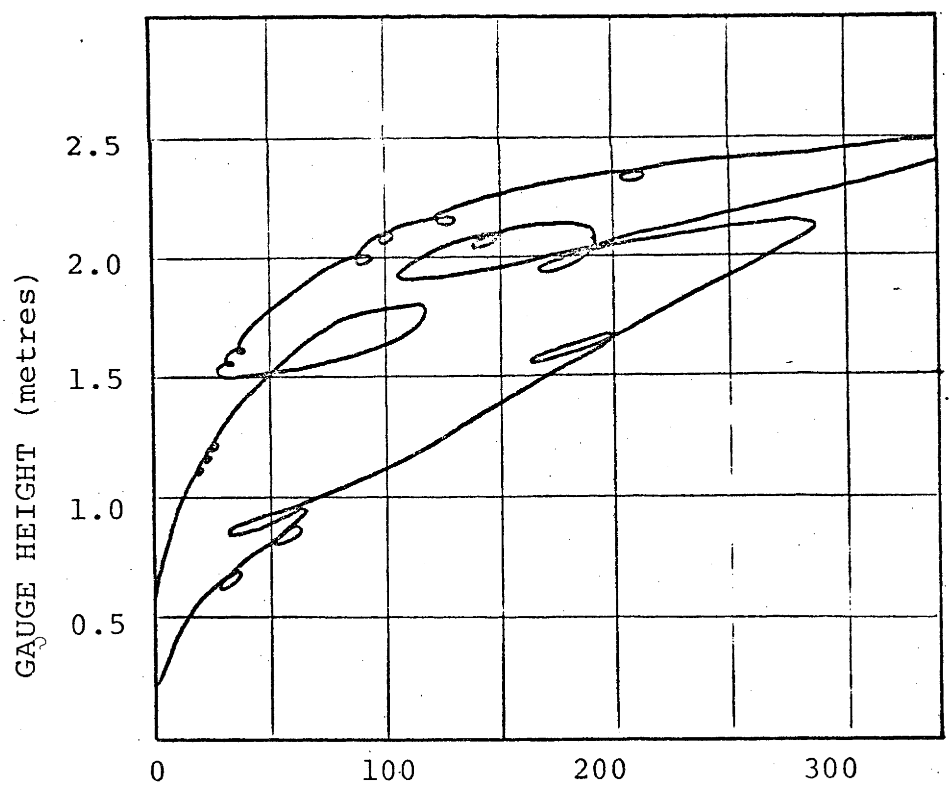

GRAPH OF CONC. AT SITE 1 VS. TIME
FOR EFFLUENT INPUT AT INJ. POINT
PLUG FLOW/CSTR MODEL
240
180
120
60
CONC.
(g/l x 10⁻⁶)
Observed Data
Model Output
Indicates range of dye concentration over 3 channels
1
2
3
4
5
TIME (hours)
(FOR TIME AFTER EFFLUENT IMPULSE ADD PURE TIME DELAY OF 3.1 HOURS)

FIG. 28



MAGELA CREEK G.S.821009

RATING CURVE



MAGELA CREEK G.S.821017

LOOP RATING CURVE

FROM: N.T. Dept. of Transport & Works
'Uranium Province Hydrology 1978

FIG. 29